A summary of the method used to provide 2019 catch limit advice for South African sardine

C.L. de Moor[*] and J.C. Coetzee[#]

Correspondence email: *carryn.demoor@uct.ac.za*

Following the declaration of Exceptional Circumstances for sardine, a TAC and TABs for sardine for 2019 were recommended based on short-term projections rather than on OMP-18. The methods used to obtain those projections are described. The Small Pelagic Scientific Working Group (SWG-PEL) focused primarily on the simulated multiplicative increase in biomass from November 2018 to 2019 under alternative 2019 catch scenarios when compared to a no catch scenario.

Introduction

South African sardine and anchovy Total Allowable Catches (TACs) and Total Allowable Bycatches (TABs) are typically recommended based on a joint Operational Management Procedure (OMP, e.g. de Moor *et al*. 2011). However, Exceptional Circumstances were declared for sardine as a result of (among other things) the very low survey estimate of sardine abundance in October-November 2018 (Figure 1). This survey estimate was outside the range simulated during the development of OMP-18 (Coetzee 2018, de Moor 2018, Figure 1). As a consequence, any TAC/TABs for sardine needed to be determined by alternative short-term calculations, rather than the OMP Harvest Control Rules (Rademeyer *et al*. 2008, de Moor 2018).

This document describes the method followed to set sardine TAC/Bs for 2019 following the declaration of Exceptional Circumstances. In short, the method involved first updating the sardine assessment to incorporate data up to November 2018 (time constraints allowed only partial checking of alternative model assumptions and precluded the calculation of posterior distributions, so that joint posterior mode results were used) and then short-term projections based on alternative constant catch scenarios were calculated.

Methods

The model used as an "initial assessment" of the resource using data from 1984 to 2018 (de Moor *et al*. 2019) is detailed in Appendix A. The assessment model considers the sardine population to consist of two mixing 'components', with a west component distributed west of Cape Agulhas and a south component distributed south-east of Cape Agulhas. Mixing occurs via movement from the west to the south component in November each year and via some contribution from the south component spawning biomass towards west component recruitment (Figure 2 of Coetzee *et al*. 2019). Recruitment is estimated independently each year with no stock-recruitment relationship estimated during conditioning.

The key model outputs and fits to data are shown in Appendix B.

Appendix C details the model used for the short-term projections. Most of the population dynamics were similar to those assumed historically except that future catch was modelled to be taken in a single annual pulse. Variability in the projections was introduced by running 100 simulations from different starting points, different future recruitments and average weights-at-length:

[*] MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.

[#] Department of Environment, Forestry and Fisheries, Private Bag X2, Vlaeberg 8018, Cape Town, South Africa.

i) The assessment provided a single set of model parameters at the joint posterior mode, including numbers-at-length (age) and biomass in November 2018 from which projections were initiated. A likelihood profile of the model predicted November survey biomass in 2018 was calculated from AD Model Builder output (Figure 2). Some variability in the November 2018 starting point for projections was thus incorporated by adjusting the numbers-at-age[1] such that, for simulation i, $1 \leq i \leq 100$, $N^{S,i}_{j,2018,a} = p_i N^S_{j,2018,a}$, where $p_i = B^{sample}_i / \left(k^S_N B^S_{j,2018}\right)$, and $B^S_{j,2018}$ denotes the model predicted total biomass in November 2018 and B^{sample}_i denotes the survey biomass sampled from the likelihood profile.

ii) Recruitment was drawn randomly from that estimated for the most recent 5 years (Figure 3).

iii) Future weight-at-length relationships were based on parameters drawn from estimates based on historical data (equation C5). No autocorrelation was assumed in the baseline (i.e. $\rho_j = 0$), given indications that the sardine condition at the beginning of 2019 was similar to that of other years rather than below average as observed during the 2018 November survey (van der Lingen *et al*. 2019).

Alternative models (hypotheses) assumed:

A) length-at-age calculated according to an annual growth curve (i.e. the length of a fish of age a in year y was dependent on the timing of recruits in year y, not the same cohort of recruits in year $y - a$),

B) autocorrelation in the future weight-at-length relationships of $\rho_{west} = 0.291$ and $\rho_{south} = 0.314$ (equation C5),

C) an alternative length frequency for the November 2018 biomass survey. The November 2018 survey length frequency may have been unrepresentative of the available population, in particular that the length frequency reflected an under sampling of larger sardine (Figure D3, Appendix D). This alternative involved reconditioning the model to the historical data where the November 2018 survey biomass observations were increased by a factor of 1.5 and the November 2018 survey biomass length frequency was taken to be a weighted average of the survey length frequency and the length frequency of commercial catches during October-December.

The sensitivity of results under these four models were tested against the following alternative assumptions:

i) higher and lower fixed proportions of 1-year-olds moving ($\mathrm{move}_{y,1} = 0.1$ and $\mathrm{move}_{y,1} = 0.5$);

ii) future recruitment generated from a hockey-stick stock recruitment relationship fit to the historically estimated effective[2] spawning biomass and recruitment time series (excluding pulse years); the hinge point is estimated to be very low, effectively implying recruitment is independent of spawning biomass;

iii) the stock weights-at-length in November 2019 were assumed to be the same as those in November 2018; and

iv) the assessment model's numbers-at-age in 2018 were decreased by 1 standard error based on the survey CVs as another means to reflect the uncertainty surrounding the recent survey estimate. This sensitivity test follows concerns of the absent May 2018 data point and the model predicting a substantially higher biomass in November 2018 than that surveyed (de Moor 2019b). The west component numbers-at-age were decreased to 1-0.3591=0.64 of the assessment point estimates and the south component numbers-at-age were decreased to 1-0.7828=0.22 of the assessment point estimates.

[1] The effective spawning biomass in 2018 was similarly adjusted for the purpose of reporting statistics only.

[2] The "effective" spawning biomass is a term which allows for a proportion (8%) of south component spawning biomass to contribute to west component recruitment by forming part of the west component "effective" spawning biomass. Recruitment to each component is assumed to be dependent on the "effective" spawning biomass of that component.

Results and Discussion

The impact of fishing on the sardine population was considered for the immediate (one-year) future as follows:

i) the additive change (increase or decrease) in effective spawning biomass from November 2018 to November 2019;

ii) the multiplicative change in effective spawning biomass from November 2018 to November 2019; and

iii) the west component effective spawning biomass in November 2019 compared multiplicatively to that in November 2007 (the sardine risk threshold)

Table E1 in Appendix E shows the results for ii) for all four models under the baseline assumptions and four alternative directed catch and bycatch scenarios. The ratio of the November 2019:2018 effective west component spawner biomass under catch/bycatch to no catch/bycatch scenarios was selected by the SWG-PEL as a key diagnostic on which to focus (Butterworth and Coetzee 2019). This ratio is given in the final column of Table E1. For this (very) short-term projection for a short-lived species the SWG-PEL focused on catch/bycatch scenarios that resulted in a ratio around 0.80. The short-term predictions under the baseline model were more optimistic than those from Alternative A, but the task team gave a higher implicit weight to the baseline model. The results from Alternative C, however, caution that the projections under the baseline may be over-optimistic. There is uncertainty surrounding the November 2018 survey length frequency and should the population have consisted of fewer recruits and more adults than estimated, short-term management advice for sardine should be more cautious. Figures E1a,b show the projected sardine effective spawning biomasses for the baseline and Alternative C models.

Tables E2a-c in Appendix E show further results for diagnostics i)-iii) above. Figure E2 graphically compares the diagnostics i)-iii) for the baseline model.

Of the sensitivity tests considered, more pessimistic projections for the west component spawning biomass resulted if movement from the west to the south was higher (as expected), if the November 2018 weight-at-length persisted during 2019 (though the task team considered that scenario to be of low probability by the time decisions were made - van der Lingen *et al*. 2019), and if the starting point in November 2018 was lower.

Based on these results, the SWG-PEL recommended the following TAC and TABs for 2019:

Directed >14cm sardine TAC	12 250t
≤14cm sardine TAB for directed >14cm sardine fishing	250t
≤14cm sardine TAB for directed anchovy fishing	9 400t
≤14cm sardine TAB for directed round herring fishing	100t
>14cm sardine TAB for directed round herring and anchovy fishing	1 000t

de Moor *et al*. (2019) list some of the primary uncertainties and concerns relating to the method followed here-in.

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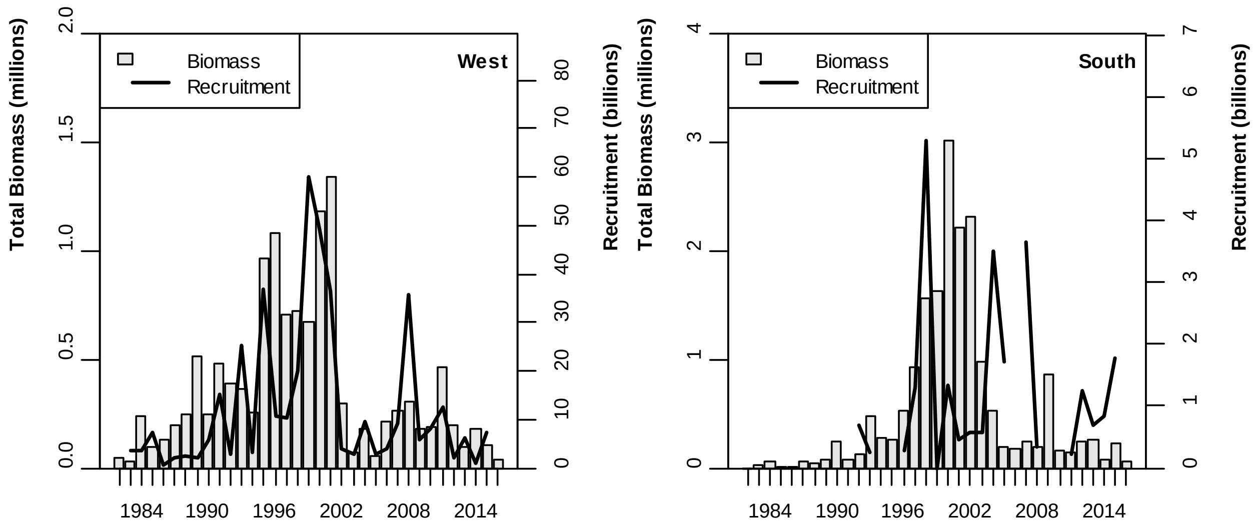


Figure 1. Acoustic survey estimated May sardine recruitment and November sardine total biomass from 1984 to 2018. The survey estimate in 2018 was 34 800t west of Cape Agulhas and 55 900t east of Cape Agulhas, while the 80 and 90% probability intervals simulated for November 2018 during OMP-18 development were [78,876] and [51,1259] thousand tons west of Cape Agulhas, [60,613] and [46,821] thousand tons east of Cape Agulhas, and [232,1333] and [176,1777] in total (de Moor 2018).

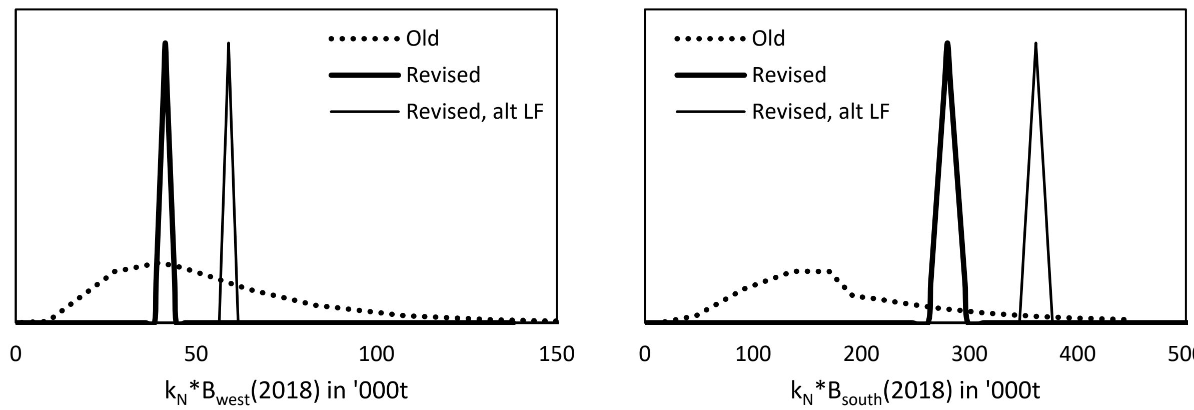


Figure 2. The likelihood profile generated by AD Model Builder for the model predicted survey biomass in November 2018 west of Cape Agulhas (left) and east of Cape Agulhas (right). “Old” – Alternative A, “Revised” – Alternative B & Baseline, “Revised, alt LF“ – Alternative C.

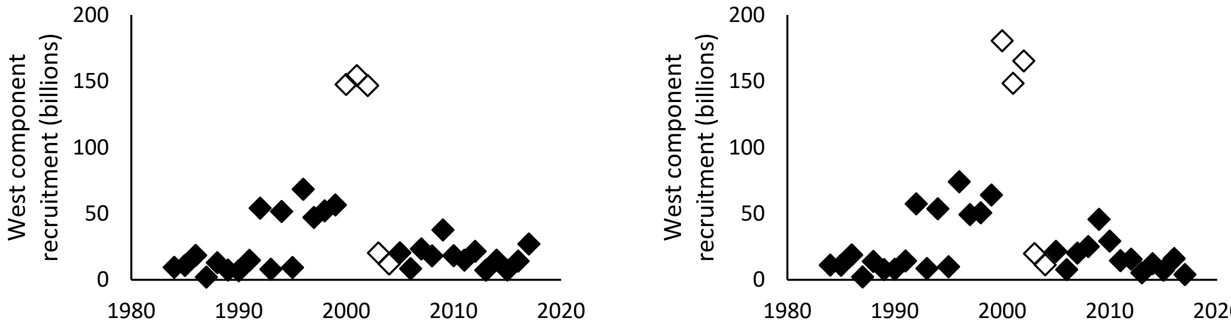


Figure 3. The model predicted west component recruitment estimated from the baseline model (left) and Alternative C (right). The autocorrelation in the time series is 0.64 (left) and 0.61 (right).

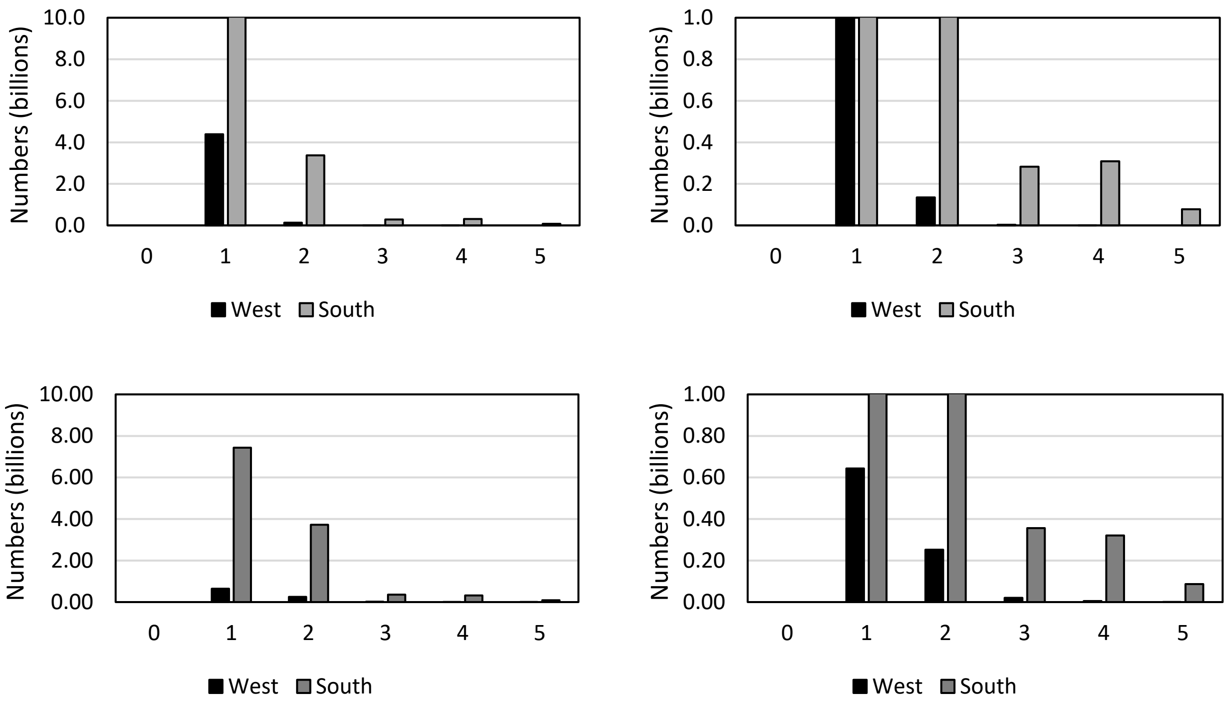


Figure 4. The point estimates of numbers-at-age in 2018 estimated by de Moor (2019b) and for Alternative C model (lower plots). The right hand plots are a repeat of the left, but with a different vertical axis range.

Appendix A: Initial 2019 assessment model for the South African sardine resource (from de Moor 2019a,b)

The assessment is run from November $y_1 = 1984$ to November $y_n = 2018$, with the following subscript notation:

- quarters $q = 1$ denoting November $y-1$ to January y, $q = 2$ denoting February to April y, $q = 3$ denoting May to July y and $q = 4$ denoting August to October y;
- ages $a = 0$ to a plus group of $a = 5^+$;
- lengths from a minus group of $l = 2.5^- cm$ to a plus group of $l = 24^+ cm$;
- components $j = W$ or $j = S$ denote the west and south components, respectively, where only the west component equations are used in the single component hypothesis;
- infection $p = NI$ or $p = I$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

All parameters are defined in Tables A1 and A2.

Population Dynamics

Numbers-at-age at 1 November before movement or infection

$$N^{S*}_{j,p,y,a} = \left(\left(\left(\left(N^S_{j,p,y-1,a-1} e^{-M^S_{y,a-1}/8} - C^S_{j,p,y,1,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,2,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,3,a-1}\right) e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,4,a-1}\right) e^{-M^S_{y,a-1}/8}$$

$$p = I, NI, y_1 \le y \le y_n, 1 \le a \le 4$$

$$N^{S*}_{j,p,y,5^+} = \left(\left(\left(\left(N^S_{j,p,y-1,4} e^{-M^S_{y,4}/8} - C^S_{j,p,y,1,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,2,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,3,4}\right) e^{-M^S_{y,4}/4} - C^S_{j,p,y,4,4}\right) e^{-M^S_{y,4}/8} +$$

$$\left(\left(\left(\left(N^S_{j,p,y-1,5^+} e^{-M^S_{y,5^+}/8} - C^S_{j,p,y,1,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,2,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,3,5^+}\right) e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,4,5^+}\right) e^{-M^S_{y,5^+}/8}$$

$$p = I, NI, y_1 \le y \le y_n \qquad \text{(A1)}$$

Infection of west component sardine in the two mixing-component hypothesis; in the single component hypothesis $I_y = 0$ as the parasite data have no influence so that they are not included in the likelihood

$$\mathrm{N}^{S**}_{W,NI,y,a} = \left(1 - \mathrm{I}_y\right)\mathrm{N}^{S*}_{W,NI,y,a} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N}^{S**}_{W,I,y,a} = \mathrm{N}^{S*}_{W,I,y,a} + \mathrm{I}_y \mathrm{N}^{S*}_{W,NI,y,a} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N}^{S**}_{S,p,y,a} = \mathrm{N}^{S*}_{S,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+ \qquad \text{(A2)}$$

Movement of west component ($j = W$) sardine to the south component ($j = S$) in the two mixing-component hypothesis; in the single component hypothesis $move_{y,a} = 0$

$$\mathrm{N}^{S}_{W,p,y,a} = \left(1 - \mathrm{move}_{y,a}\right)\mathrm{N}^{S**}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N}^{S}_{S,p,y,a} = \mathrm{N}^{S**}_{S,p,y,a} + \mathrm{move}_{y,a}\mathrm{N}^{S**}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+ \qquad \text{(A3)}$$

Numbers-at-age mid-way through each quarter (for use in catch equations)

$$N^S_{j,p,y,1,a} = N^S_{j,p,y-1,a} e^{-M^S_{y,a}/8} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

$$N^S_{j,p,y,q,a} = \left(N^S_{j,p,y,q-1,a} - C^S_{j,p,y,q-1}\right) e^{-M^S_{y,a}/4} \qquad p = I, NI, y_1 \le y \le y_n, 2 \le q \le 4, 0 \le a \le 5^+ \quad \text{(A4)}$$

Numbers-at-length at 1 November (after infection and movement)

The model estimated numbers-at-length range from a 2.5cm minus group to a 24cm plus group, denoted 2.5[-] and 24[+], respectively, in the remaining text.

$$N^{S}_{j,p,y,l} = \sum_{a=0}^{5^+} A^{sur}_{j,y,a,l} N^{S}_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^{-}cm \le l \le 24^{+}cm \quad \text{(A5)}$$

The model predicted numbers-at-length of ages 1+ only are given by:

$$N^{S,1+}_{j,p,y,l} = \sum_{a=1}^{5^+} A^{sur}_{j,y,a,l} N^{S}_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^{-}cm \le l \le 24^{+}cm \quad \text{(A6)}$$

The proportion of sardine of age a in component j that fall in length group l at 1 November, $A^{sur}_{j,y,a,l}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A^{sur}_{j,y,a,l} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j(a - t_{0,j,y-a})}\right), \vartheta_a^2\right)^{3} \qquad y_1 \le y \le y_n,\ 0 \le a \le 5^+,\ 2.5^{-}cm \le l \le 24^{+}cm \quad \text{(A7)}$$

with

$$t_{0,j,y} = \begin{cases} t_{0,j} + \varepsilon^t_y & y = y_1 \\ t_{0,j} + \rho^t \varepsilon^t_{y-1} + \sqrt{1-(\rho^t)^2}\,\varepsilon^t_y & y_1 < y \le y_n \end{cases}^{4} \qquad \text{(A8)}$$

Natural mortality

Natural mortality is modelled to vary annually in an autocorrelated manner around a median as follows (although the baseline assumes no such correlation – see Table A.1):

$$M^{S}_{y,a=0} = \bar{M}^{S}_{ju} e^{\varepsilon^{ju}_y} \text{ with } \varepsilon^{ju}_{1984} = \eta^{ju}_{1984} \text{ and } \varepsilon^{ju}_y = \rho\varepsilon^{ju}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ju}_y,\ y_1 \le y \le y_n \quad \text{(A9)}$$

$$M^{S}_{y,a=1+} = \bar{M}^{S}_{ad} e^{\varepsilon^{ad}_y} \text{ with } \varepsilon^{ad}_{1984} = \eta^{ad}_{1984} \text{ and } \varepsilon^{ad}_y = \rho\varepsilon^{ad}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ad}_y,\ y_1 \le y \le y_n \quad \text{(A10)}$$

Spawning biomass and biomass associated with the November survey

$$SSB^{S}_{j,y} = \sum_p \sum_{l=2.5^-}^{24^+} f^{S}_{j,y,l} N^{S,1+}_{j,p,y,;} w^{S}_{j,y,l} \qquad y_1 \le y \le y_n \quad \text{(A11)}$$

$$SSB^{eff,S}_{j=W,y} = \xi_W SSB^{S}_{W,y} + (1-\xi_S) SSB^{S}_{S,y} \qquad y_1 \le y \le y_n$$

$$SSB^{eff,S}_{j=S,y} = (1-\xi_W) SSB^{S}_{W,y} + \xi_S SSB^{S}_{S,y} \qquad y_1 \le y \le y_n \quad \text{(A12)}$$

$$B^{S}_{j,y} = k^{S}_{j,N} \sum_p \sum_{l=2.5^-}^{24^+} N^{S}_{j,p,y,l} w^{S}_{j,y,l}\ ^{5} \qquad y_1 \le y \le y_n \quad \text{(A13)}$$

where $w^{S}_{j,y,l} = w^{S}_{j,l} \times \frac{\tilde{w}_{j,y}}{\left(\sum_p \sum_{l=2.5^-}^{24^+} N^{S,1+}_{j,p,y,l} w^{S}_{j,l}\right) / \left(\sum_p \sum_{l=2.5^-}^{24^+} N^{S,1+}_{j,p,yl;}\right)}$ $\qquad y_1 \le y \le y_n,\ 2.5^{-}cm \le l \le 24^{+}cm \quad$ (A14)

Commercial selectivity

$$S_{j,y,q,l} = \begin{cases} 0 & l \le 5.5cm \\ \chi_j exp\left\{-\frac{\left(l + 0.25 - \bar{l}_{1,j}\right)^2}{(\sigma^{sel}_1)^2}\right\} + \frac{1}{1 + exp\left\{-\left(l + 0.25 - \bar{l}_{2,j,y,q}\right)/(\sigma^{sel}_2)^2\right\}} & 6cm \le l \le l_{max} = 23cm\ ^{6} \\ S_{j,y,q,lmax} & l > l_{max} \end{cases}$$

$$y_1 \le y \le y_n,\ 1 \le q \le 4 \quad \text{(A15)}$$

[3] Given the allowance for early/late recruitment in varying $t_{0,y}$ estimates annually, there may be some proportion of this distribution below a length of zero (due to late recruitment). In these cases, this proportion is removed from the proportion-at-length of the minus length class.

[4] Additive error allows for early or late recruitment. While the timing of recruitment may vary between stocks due to differing environmental conditions on the west and south coasts, the same autocorrelation parameters are assumed here for simplicity reasons.

[5] The biomass in $y_n = 2018$ excludes age 0 fish, although the contribution of age 0 fish to the total biomass should be minor.

[6] The $l + 0.25$ denotes the middle of length class l. This function is renormalized to a maximum of 1.

$$S_{j,y,q,a} = \sum_{l=2.5^-}^{24^+} A_{j,y,q,a,l}^{com} S_{j,y,q,l} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4,\ 0 \le a \le 5^+ \qquad \text{(A16)}$$

where $A_{j,y,q,a,l}^{com} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j\left(a+(2q-1)/8 - t_{0,j,y-a}\right)}\right), \left[\left(1 - \frac{(2q-1)}{8}\right)\vartheta_a + \frac{(2q-1)}{8}\vartheta_{a+1}\right]^2\right)$

$$y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A17)}$$

Bycatch in the anchovy directed fishery

$$C_{j,p,y,q,a}^{bycatch} = \begin{cases} N_{j,p,y,q,a}^S F_{j,y,q,a}^{By} & 0 \le a \le 1 \\ 0 & 2 \le a \le 5^+ \end{cases} {}^{7} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4 \qquad \text{(A18)}$$

Catch in the directed sardine and round herring bycatch fisheries

$$C_{j,p,y,q,a}^{dir} = \left(N_{j,p,y,q,a}^S - C_{j,p,y,q,a}^{bycatch}\right) S_{j,y,q,a} F_{j,y,q} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A19)}$$

Total catch

$$C_{j,p,y,q,a}^{S} = C_{j,p,y,q,a}^{bycatch} + C_{j,p,y,q,a}^{dir} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A20)}$$

Fished proportion of the available biomass from the sardine bycatch with the anchovy directed fishery

$$F_{j,y,q=1,a=0}^{By} = \frac{\sum_{m=11}^{12} \sum_{l<lcut_{y-1,m}} C_{j,y-1,m,l}^{RLF,fleet=3} + \sum_{l<lcut_{y,m}} C_{j,y,1,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=1,a=0}^S}$$

$$F_{j,y,q=1,a=1}^{By} = \frac{\sum_{m=11}^{12} \sum_{l\ge lcut_{y-1,m}} C_{j,y-1,m,l}^{RLF,fleet=3} + \sum_{l\ge lcut_{y,m}} C_{j,y,1,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=1}^S}$$

$$F_{j,y,q=2,a=0}^{By} = \frac{\sum_{m=2}^{4} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=2,a=0}^S} \qquad F_{j,y,q=2,a=1}^{By} = \frac{\sum_{m=2}^{4} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=2,a=1}^S}$$

$$F_{j,y,q=3,a=0}^{By} = \frac{\sum_{m=5}^{7} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=3,a=0}^S} \qquad F_{j,y,q=3,a=1}^{By} = \frac{\sum_{m=5}^{7} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=3,a=1}^S}$$

$$F_{j,y,q=4,a=0}^{By} = \frac{\sum_{m=8}^{10} \sum_{l<lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=0}^S} \qquad F_{j,y,q=4,a=1}^{By} = \frac{\sum_{m=8}^{10} \sum_{l\ge lcut_{y,m}} C_{j,y,m,l}^{RLF,fleet=3}}{\sum_p N_{j,p,y,q=4,a=1}^S} \qquad \text{(A21)}$$

A penalty is imposed within the model to ensure that $F_{j,y,q,a}^{By} < 0.95$.

Fished proportion of the available biomass from the directed sardine catch and sardine bycatch with round herring fishery

$$F_{j,y,q=1} = \frac{\sum_{fleet=1}^{2} \sum_{m=11}^{12} \sum_{l\ge 6cm} C_{j,y-1,m,l}^{RLF,fleet} + \sum_{fleet=1}^{2} \sum_{l\ge 6cm} C_{j,y,1,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,1,a}^S - C_{j,y,1,a}^{bycatch}\right) S_{j,y,1,a}}$$

$$F_{j,y,q=2} = \frac{\sum_{fleet=1}^{2} \sum_{m=2}^{4} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,2,a}^S - C_{j,y,2,a}^{bycatch}\right) S_{j,y,2,a}}$$

$$F_{j,y,q=3} = \frac{\sum_{fleet=1}^{2} \sum_{m=5}^{7} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,3,a}^S - C_{j,y,3,a}^{bycatch}\right) S_{j,y,3,a}}$$

$$F_{j,y,q=4} = \frac{\sum_{fleet=1}^{2} \sum_{m=8}^{10} \sum_{l\ge 6cm} C_{j,y,m,l}^{RLF,fleet}}{\sum_p \sum_{a=0}^{5+} \left(N_{j,p,y,4,a}^S - C_{j,y,4,a}^{bycatch}\right) S_{j,y,4,a}} \qquad \text{(A22)}$$

[7] "Selectivity" is incorporated in $F_{j,y,q,a}^{By}$, as the sardine bycaught is typically independent of sardine abundance, but rather correlated with anchovy recruitment which varies from year to year.

A penalty is imposed within the model to ensure that $S_{j,y,a,l}F_{j,y,q} < 0.95$. Fish <6cm were seldom[8] caught and were thus not used in fitting this model. Commercial selectivity-at-length is fixed to zero for length classes <6cm (equation A12).

Number of recruits associated with the recruit survey

$$N^S_{j,y,r} = k^S_{j,r}\left(\left(N^S_{j,NI,y,2,0} - C^S_{j,NI,y,2,0}\right)e^{-\left(1/8+0.5t^S_y/12\right)M^S_{y,0}} - \tilde{C}^S_{j,y,0bs}\right)e^{-0.5t^S_y \times M^S_{y,0}/12} \quad 1985 \le y \le y_n \quad \text{(A23)}$$

Multiplicative survey bias

$$k^S_{j,N} = k^S_{ac} \quad \text{(A24)}$$

$$k^S_{j=W,r} = k^S_{cov} \times k^S_{ac} \quad \text{(A25)}$$

$k^S_{j=S,r} = k^S_{covS} \times k^S_{cov} \times k^S_{ac}$ (for the two mixing-component hypothesis only) (A26)

Survey trawl selectivity

$$S^{survey}_{j,l} = \begin{cases} 0 & l = 2.5^- cm \\ \left[1 + exp\left\{-\left(l + 0.25 - S_{50,j}\right)/\delta_j\right\}\right]^{-1} & 3cm \le l \le 24^+ cm \end{cases} \quad y_1 \le y \le y_n \text{(A27)}$$

Proportion-at-length associated with the November survey

$$p^S_{j,y,l} = \begin{cases} \dfrac{\sum_p \sum_{l \le 6cm} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 6^- cm \\ \dfrac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & 6.5cm \le l \le 20.5cm \\ \dfrac{\sum_p \sum_{l=21}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 21 - 23.5cm \\ \dfrac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,24^+}}{\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} S^{survey}_{j,l}} & l = 24^+ cm \end{cases} {}^{9} \quad y_1 \le y \le y_n \quad \text{(A28)}$$

Proportion-at-length of fish infected with the parasite in November

$$P^S_{j,y,l} = \frac{N^S_{j,I,y,l}}{\sum_p N^S_{j,p,y,l}} \quad y_1 \le y \le y_n, 10cm \le l \le 23cm \quad \text{(A29)}$$

Catch-at-length from the directed and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5^+}\left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right)A^{com}_{j,q,a,l} S_{j,y,q,l} F_{j,y,q} \; {}^{10}$$

$$p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4,\ 2.5^- cm \le l \le 24^+ cm \quad \text{(A30)}$$

[8] Less than 6% of the quarters west of Cape Agulhas, less than 2% of the quarters south-east of Cape Agulhas and less than 4% of the quarters for the whole coast.
[9] The inclusion of model predicted proportion-at-length 24⁺cm is deliberate to take into account the zero samples of 24⁺cm sardine in the survey.
[10] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

Proportion-at-length associated with the directed catch and round herring bycatch

$$p_{j,y,q,l}^{coml,S} = \begin{cases} \frac{\sum_p C_{j,p,y,q,l}^{dir}}{\sum_p \sum_{l=6}^{24^+} C_{j,p,y,q,l}^{dir}} & 6cm \le l \le 22.5cm \\ \frac{\sum_p \sum_{l=23}^{24^+} C_{j,p,y,q,l}^{dir}}{\sum_p \sum_{l=6}^{24^+} C_{j,p,y,q,l}^{dir}} & l = 23^+cm \end{cases} \quad [11] \quad y_1 \le y \le y_n, 1 \le q \le 4 \tag{A31}$$

<u>Fitting the Model to Observed Data (Likelihood)</u>

$$-lnL = -lnL^{Nov} - lnL^{rec} - lnL^{sur\ propl} - lnL^{com\ propl} - lnL^{prev} \tag{A32}$$

where

$$-lnL^{Nov} = 0.5 \sum_j \sum_{y=y_1}^{y_n} \left\{ \frac{5^5 \left(\frac{\left| ln\left(\hat{B}_{j,y}^S\right) - ln\left(B_{j,y}^S\right) \right|}{\sqrt{\left(\sigma_{j,y,Nov}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,N}^S\right)^2}} \right)^5}{5^5 + \left(\frac{\left| ln\left(\hat{B}_{j,y}^S\right) - ln\left(B_{j,y}^S\right) \right|}{\sqrt{\left(\sigma_{j,y,Nov}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,N}^S\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi\left(\left(\sigma_{j,y,Nov}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,N}^S\right)^2\right)\right] \tag{A33}$$

$$-lnL^{rec} = 0.5 \sum_j \sum_{y=y_2}^{y_n} \left\{ \frac{5^5 \left(\frac{\left| ln\left(\hat{N}_{j,y,r}^S\right) - ln\left(N_{j,y,r}^S\right) \right|}{\sqrt{\left(\sigma_{j,y,rec}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,r}^S\right)^2}} \right)^5}{5^5 + \left(\frac{\left| ln\left(\hat{N}_{j,y,r}^S\right) - ln\left(N_{j,y,r}^S\right) \right|}{\sqrt{\left(\sigma_{j,y,rec}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,r}^S\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi\left(\left(\sigma_{j,y,rec}^S\right)^2 + \left(\phi_{ac}^S\right)^2 + \left(\lambda_{j,r}^S\right)^2\right)\right] \tag{A34}$$

$$-lnL^{sur\ propl} = w_{propl}^{sur} \sum_j \sum_{y=y_1}^{y_n} \left\{ \sum_{l=6^-}^{21^+} \left\{ \frac{\left(\sqrt{\hat{p}_{j,y,l}^S} - \sqrt{p_{j,y,l}^S}\right)^2}{2\left(\sigma_{j,sur}^S\right)^2} + ln\left(\sigma_{j,sur}^S\right) \right\} + \frac{\left(0 - \sqrt{p_{j,y,24^+}^S}\right)^2}{2\left(\sigma_{j,sur}^S\right)^2} + ln\left(\sigma_{j,sur}^S\right) \right\} \quad [12] \tag{A35}$$

$$-lnL^{com\ propl} = w_{propl}^{com} \sum_j \sum_{y=y_1}^{y_n} \sum_{q=1}^{4} \sum_{l=6}^{23^+} \left\{ \frac{\left(\sqrt{\hat{p}_{j,y,q,l}^{S,coml}} - \sqrt{p_{j,y,q,l}^{S,coml}}\right)^2}{2\left(\sigma_{j,com}^S\right)^2} + ln\left(\sigma_{j,com}^S\right) \right\} \tag{A36}$$

$$-lnL^{prev} = \sum_j \sum_{y=2010}^{2018} \sum_{l=10cm}^{23cm} -n_{j,y,l}^{prev} ln\left(P_{j,y,l}^S\right) - \left(N_{j,y,l}^{prev} - n_{j,y,l}^{prev}\right) ln\left(1 - P_{j,y,l}^S\right) \tag{A37}$$

A "robustified likelihood" is used for the contributions from the hydro-acoustic surveys to ensure no undue influence from any extreme (outlying) values for residuals. The functional form chosen to robustify makes negligible difference for standardised residuals of magnitude three or less, but essentially treats large standardised residuals as if they do not exceed five in magnitude.

[11] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

[12] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.

Table A1. Assessment model parameters and variables with associated fixed values or prior distributions and, for derived variables, associated equation numbers. As the majority of prior distributions are uninformative, notes are provided only for informative priors and/or bounds.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N^S_{j,p,y,a}$	Model predicted numbers-at-age a at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions	$ln(N^S_{j,NI,y,0})/10 \sim U(-10,3.$ $N^S_{j,I,y,0} = 0$	A1 - A3	
	$N^S_{j,p,1983,a}$	Initial numbers-at-age a in component j	Billions	$N^S_{j,NI,1983,a=1} \sim U(0,50)$ $N^S_{j,NI,1983,a} = 0, 2 \leq a \leq 5^+$ $N^S_{j,I,1983,a} = 0, 0 \leq a \leq 5^+$		
	$N^S_{j,p,y,q,a}$	Model predicted numbers-at-age a mid-way through quarter q of year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A4	
	I_y	Proportion of uninfected west component sardine that are infected with the endoparasite in year y (two mixing-component hypothesis only)		$= 0, y_1 \leq y \leq 2007$ $\sim U(0,1), 2008 \leq y \leq y_n$		
	$move_{y,a}$	Proportion of west component sardine of age a which move to the south component at the beginning of November of year y (two mixing-component hypothesis only)	-	$move_{y,1} \sim Beta(1.05,1.05)$ $move_{y,2+} = \phi move_{y,1}$ $\phi \sim U(0,1)$		
	$SSB^S_{j,y}$	Model predicted spawning biomass of component j at the beginning of November in year y	Thousand tons		A11	
	$SSB^{eff,S}_{j,y}$	Model predicted effective spawning biomass of component j at the beginning of November in year y	Thousand tons		A12	
	$B^S_{j,y}$	Model predicted total biomass of component j at the beginning of November in year y, associated with the November survey	Thousand tons		A13	
	ξ_j	Proportion of j-component spawner biomass that contributes to the effective spawning biomass on the same coast		0.08		Alternative values considered in robustness tests
	$w^S_{j,l}$	Mean mass of sardine of component j in length class l	Grams	$1.1639 \times 10^{-5} \times l^{3.03155}$		van der Lingen *et al.* (2006)
	$w^S_{j,y,l}$	Mean mass of sardine of component j in length class l at the beginning of November in year y	Grams		A14	
	$\widetilde{w}^S_{j,y}$	Mean mass of sardine sampled from component j during the November survey of year y	Grams	$\frac{\sum_{l=3}^{23.5} N^{S,obs}_{j,y,l} w^S_{j,l}}{\sum_{l=3}^{23.5} N^{S,obs}_{j,y,l}}$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$f_{j,y,l}^S$	Proportion of component j sardine that are mature in length class l in year y	-	$\left[1+e^{-(l-17.2)/1.17}\right]^{-1}$ $1984 \leq y \leq 1987$ $\left[1+e^{-(l-18.6)/1.26}\right]^{-1}$ $1988 \leq y \leq 1995$ $\left[1+e^{-(l-19.4)/1.40}\right]^{-1}$ $1996 \leq y \leq 2003$ $\left[1+e^{-(l-17.4)/0.95}\right]^{-1}$ $2004 \leq y \leq 2018$		Refit from data used by van der Lingen *et al*. (2006) using midpoints of length classes. Assuming maturity post-2003 reflects that of 1965-1975 as maturity is hypothesized to be density dependent (van der Lingen *et al*. 2006) and both these periods correspond to low biomass following a peak in abundance
	$N_{j,y,r}^S$	Model predicted number of juveniles of component j at the time of the recruit survey in year y	Billions		A23	
Natural mortality	$M_{y,a}^S$	Rate of natural mortality of age a in year y	Year^{-1}	$M_{y,0}^S = 1.0$ $M_{y,1+}^S = 1.0$	A9 and A10	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\bar{M}_{ju}^S$	Median juvenile rate of natural mortality	Year^{-1}	1.0		
	$\bar{M}_{ad}^S$	Median rate of natural mortality for 1+ sardine	Year^{-1}	0.8		
	ε_y^{ju}	Annual residuals about juvenile natural mortality rate	-		A9	
	ε_y^{ad}	Annual residuals about natural mortality rate for 1+ sardine	-		A10	
	η_y^{ju}	Normally distributed error in calculating ε_y^{ju}	-	$N(0, \sigma_j^2)$		
	η_y^{ad}	Normally distributed error in calculating ε_y^{ad}	-	$N(0, \sigma_{ad}^2)$		
	σ_j	Standard deviation in the annual residuals about juvenile natural mortality	-	0		See robustness tests
	σ_{ad}	Standard deviation in the annual residuals about natural mortality for ages 1+	-	0		See robustness tests
	ρ	Annual autocorrelation coefficient	-	0		See robustness tests

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Proportions-at-length and growth curve	$N^S_{j,p,y,l}$	Model predicted numbers-at-length l at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A5	
	$p^S_{j,y,l}$	Model predicted proportion-at-length l of component j associated with the November survey in year y	-		A28	
	$A^{sur}_{j,y,a,l}$	Proportion of age a of component j sardine that falls in the length group l in November of year y	-		A7	
	κ_j	Somatic growth rate parameter for component j	Year^{-1}	$U(0,3)$		
	$L_{j,\infty}$	Maximum length (in expectation) of component j	Cm	$L_{j,\infty} = \frac{L_{j,1}e^{-2\kappa_j}-L_{j,3}}{e^{-2\kappa_j}-1}$ where $L_{j,a=1} \sim U(5,25)$ $L_{j,a=3} - L_{j,a=1} \sim U(5,25)$		
	$t_{0,j,y}$	Age at which the length (in expectation) is zero in year y	Year		A8	
	$t_{0,j}$	Average age at which the length (in expectation) is zero	Year	$\frac{1}{\kappa_j} ln\left\{\frac{e^{\kappa_j}(L_{j,1} - L_{j,3})}{L_{j,1}e^{-2\kappa_j} - L_{j,3}}\right\}$		
	ε^t_y	Annual residuals about the age at which the length is zero		$N(0,2)$		
	ρ^t	Autocorrelation coefficient in these residuals		$U(-1,1)$		
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$U(0,3)$, $a = 0,1,2^+$		Upper bound chosen to preclude unrealistically large lengths for very young fish
	$p^{com,S}_{j,y,q,l}$	Model predicted proportion-at-length l of component j in the directed catch and round herring bycatch during quarter q of year y	-		A31	
	$A^{com}_{j,y,q,a,l}$	Proportion of age a of component j sardine that falls in the length group l mid-way through quarter q of year y	-		A17	
	$P^S_{j,y,l}$	Model predicted proportion-at-length l of component j that are infected with the endoparasite, at the time of the November survey in year y			A29	

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Selectivity	$S_{j,l}^{survey}$	Survey selectivity-at-length l in the November survey for component j	-		A27	Some smaller fish escape through the trawl net
	$S_{50,j}$	Length at which survey selectivity is 50% for component j	Cm	$U(2.5,20)$		
	δ_j	Inverse of slope of survey selectivity-at-length ogive when selectivity is 50% for component j	-	$U(0.05,50)$		
	$S_{j,y,q,l}$	Commercial selectivity-at-length l during quarter q of year y of component j	-		A15	
	$S_{j,y,q,a}$	Commercial selectivity-at-age a during quarter q of year y of component j	-		A16	
	χ_j	Height of the Gaussian component for component j relative to the height of the logistic component	-	$U(0,1)$		
	$\bar{l}_{1,j}$	Mean of the Gaussian distribution for component j	Cm	$U(5,15)$		
	$\bar{l}_{2,j,y,q}$	Length at 50% selectivity in the logistic component for component j in quarter q of year y	Cm	$\bar{l}_{2,j,y,q} - \bar{l}_{1,j} \sim U(0,15)$		Estimated for four time periods 84-86, 87-97, 98-01, 02-18
	$(\sigma_1^{sel})^2$	Variance parameter of the Gaussian distribution	Cm	$U(2,7)$		
	$(\sigma_2^{sel})^2$	Variance parameter of the logistic distribution	Cm	$U(0,10)$		
Multiplicative bias	$k_{j,N}^S$	Multiplicative bias associated with the November survey of component j	-		A24	
	$k_{j,r}^S$	Multiplicative bias associated with the recruit survey of component j	-		A25 – A26	
	k_{ac}^S	Multiplicative bias associated with the hydro-acoustic survey	-	$ln(k_{ac}^S) \sim N(-0.311, 0.094^2)$		Appendix B of de Moor and Butterworth (2016)
	k_{cov}^S	Multiplicative bias associated with the coverage of the recruits during the recruit survey in comparison to the coverage of the biomass during the November survey	-	Uniform prior on logit transpose of k_{cov}^S, such that $0.3 \leq k_{cov}^S \leq 1$		Lower bound selected in discussions with scientists on these surveys and their field experience
	k_{covS}^S	Multiplicative bias associated with the coverage of the south component recruits in comparison to the west component recruits during the recruit survey		$U(0,1)$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Catch	$C^{S}_{j,p,y,q,a}$	Model predicted number of age a fish of component j caught during quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A20	
	$lcut_{y,m}$	Cut off length for recruits in month m of year y	Cm	de Moor *et al*. 2019		Differ by month and year as informed by the recruit surveys
	$C^{bycatch}_{j,p,y,q,a}$	Number of age a fish of component j bycaught in the anchovy-directed fishery in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A18	
	$C^{dir}_{j,p,y,q,a}$	Number of age a fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A19	
	$C^{dir}_{j,p,y,q,l}$	Number of length l fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y	Billions		A30	
	$F^{By}_{j,y,q,a}$	Fished proportion in quarter q of year y for age class a of component j, of bycatch in the anchovy-directed fishery	-		A21	
	$F_{j,y,q}$	Fished proportion in quarter q of year y for a fully selected age class a of component j, by the directed and round herring bycatch fisheries	-		A22	
Likelihood	$-lnL^{Nov}$	Contribution to the negative log likelihood from the model fit to the November survey biomass data	-		A33	
	$-lnL^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A34	
	$-lnL^{surpropl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A35	
	$-lnL^{compropl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A36	
	$-lnL^{surprev}$	Contribution to the negative log likelihood from the model fit to the November parasite prevalence-at-length data	-		A37	
	ϕ^{S}_{ac}	CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually rather than remain fixed over time	-	=0.227		Appendix B of de Moor and Butterworth (2016)
	$\left(\lambda^{S}_{j,N/r}\right)^2$	Additional variance (over and above $\left(\sigma^{S}_{j,y,Nov/rec}\right)^2$ and $(\phi^{S}_{ac})^2$) associated with the November/recruit surveys of component j	-	$U(0,10)$		

Table A1 (Continued).

Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
w_{propl}^{sur}	Weighting applied to the remaining survey proportion-at-length data	-	$= 0.5 \times 0.167$		To allow for autocorrelation[13]
$\sigma_{j,sur}^{S}$	Standard deviation associated with the survey proportion-at-length data of component j	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}\left(\sqrt{\hat{p}_{j,y,l}^{S}}-\sqrt{p_{j,y,l}^{S}}\right)^2}{\sum_{y=y_1}^{y_n}\sum_{l=6^-}^{21^+}1}}$ [14]		Closed form solution
w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data		$= 0.5 \times 0.04$		To allow for autocorrelation[15]
$\sigma_{j,com}^{S}$	Standard deviation associated with the commercial proportion-at-length data of stock j	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}\left(\sqrt{\hat{p}_{j=1,y,q,l}^{comlS}}-\right.}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}1}}$ $\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}\left(\sqrt{\hat{p}_{j=2,y,q,l}^{comlS}}-\right.}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}1}}$	Closed form solution[16]	$\sigma_{j,com}^{S}$

[13] Based upon data being available ~6 times more frequently than annual age data which contain maximum information content on this.
[14] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.
[15] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this.
[16] A shorter range of lengths is used for the south component given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

Table A2. Assessment model data, detailed in de Moor *et al*. (2019).

Quantity	Description	Units / Scale	Shown in Figure
t_y^S	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\tilde{C}_{j,y,0bs}^S$	Number of juveniles of component j caught between 1 May and the day before the start of the recruit survey in year y	Billions	
$C_{j,y,m,l}^{RLF,fleet}$	Number of fish in length class l landed by $fleet$ in month m of year y of component$j$. $fleet = 1$ denotes the sardine directed fishery, $fleet = 2$ denotes the sardine bycatch with round herring (1984-2011) or ≥14cm sardine bycatch (2012-18) and $fleet = 3$ denotes the juvenile sardine bycatch with anchovy (1984-2011) or <14cm sardine bycatch (2012-18)	Billions	
$\hat{B}_{j,y}^S$	Acoustic survey estimate of biomass of component j from the November survey in year y	Thousand tons	Fig. 1
$\sigma_{j,y,Nov}^S$	Survey sampling CV associated with $\hat{B}_{j,y}^S$ that reflects survey inter-transect variance	-	Fig. 1
$\hat{N}_{j,y,r}^S$	Acoustic survey estimate of recruitment of component j from the recruit survey in year y	Billions	Fig. 2
$\sigma_{j,y,rec}^S$	Survey sampling CV associated with $\hat{N}_{j,y,r}^S$ that reflects survey inter-transect variance	-	Fig. 2
$\hat{p}_{j,y,l}^S$	Observed proportion (by number) of component j in length group l in the November survey of year y	-	Fig. 6
$\hat{p}_{j,y,q,l}^{S,com}$	Observed proportion (by number) of the directed catch and round herring bycatch of fish of component j and length group l during quarter q of year y	-	Fig. 9
$n_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested and found to be infected with the endoparasite	Numbers	Fig. 13
$N_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested for infection with the endoparasite	Numbers	Fig. 13

Appendix B. Results from the assessment detailed in Appendix A (from de Moor 2019b).

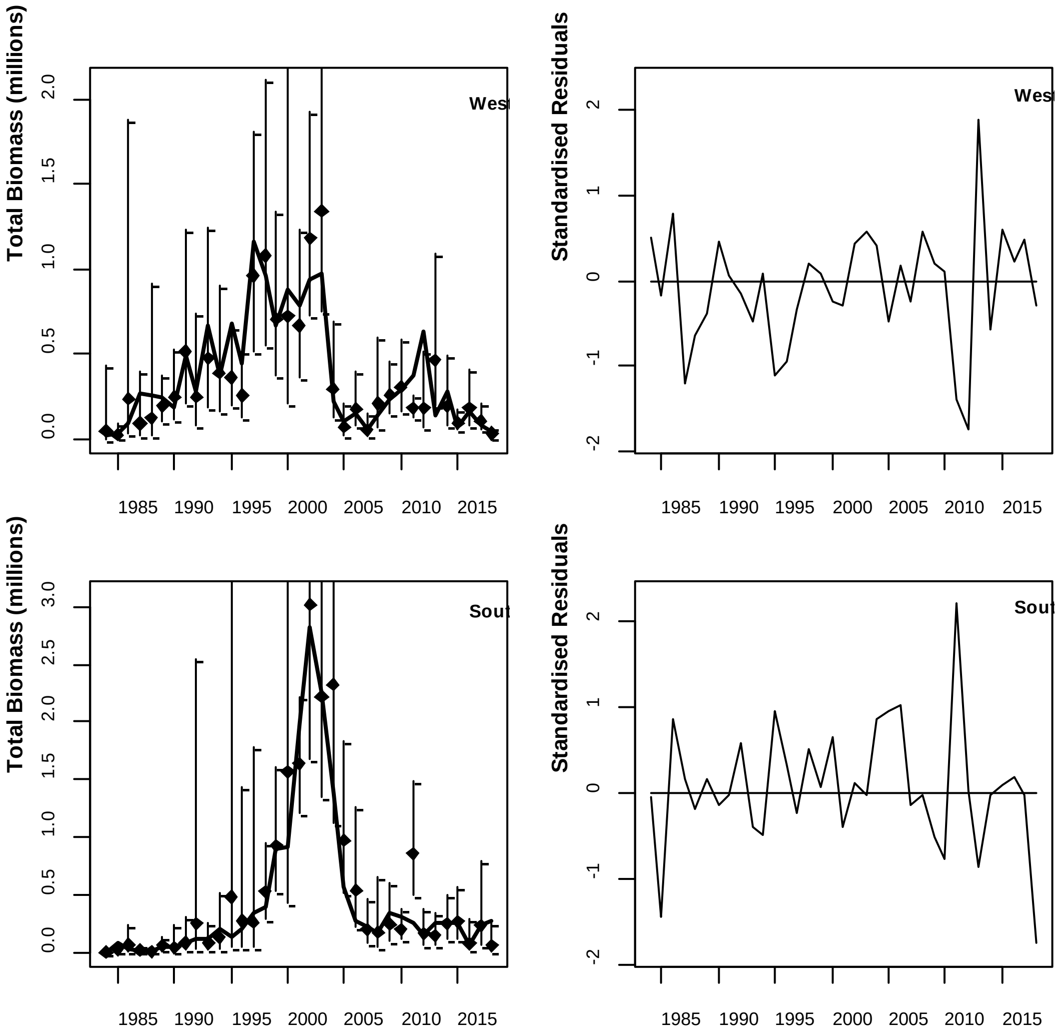


Figure B1. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2018. The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots.

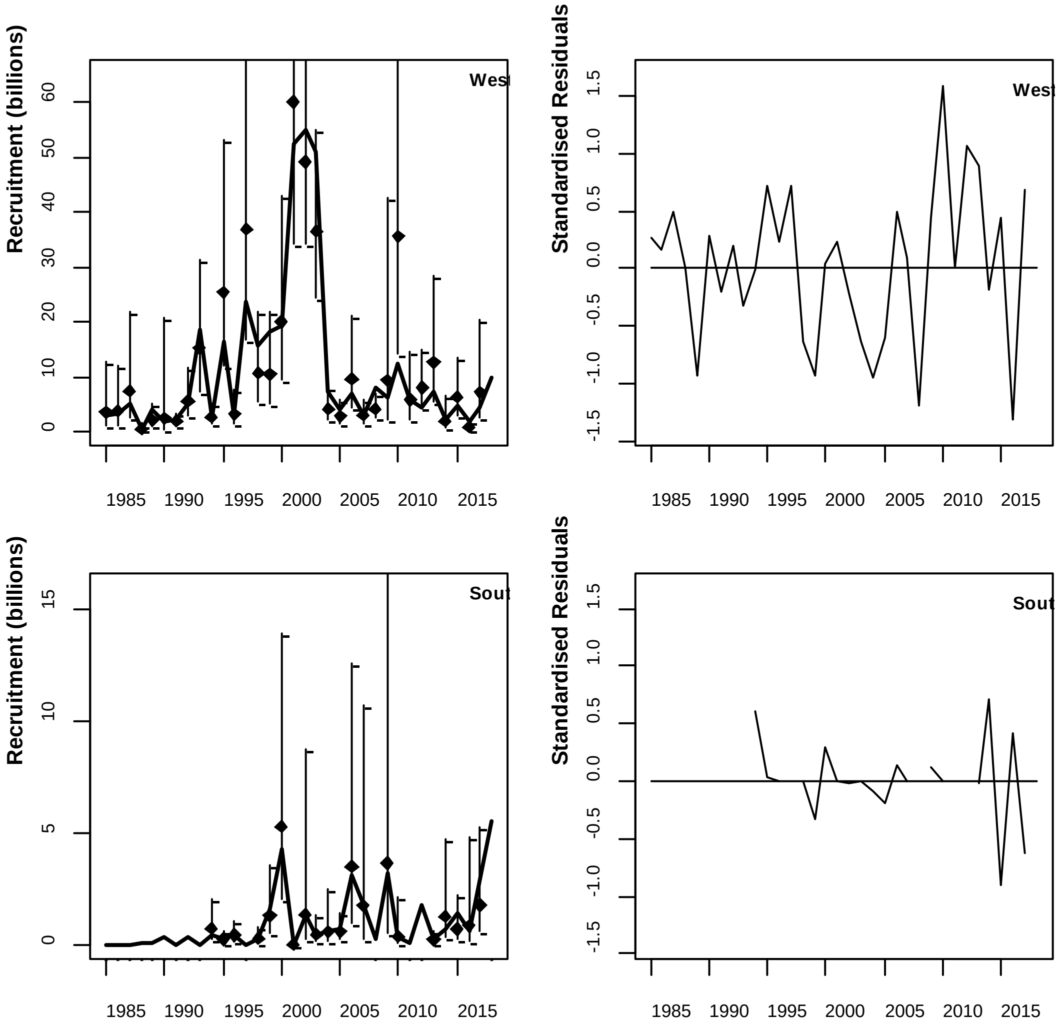


Figure B2. Acoustic survey estimated and model predicted sardine recruitment numbers from May 1985 to May 2018. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots.

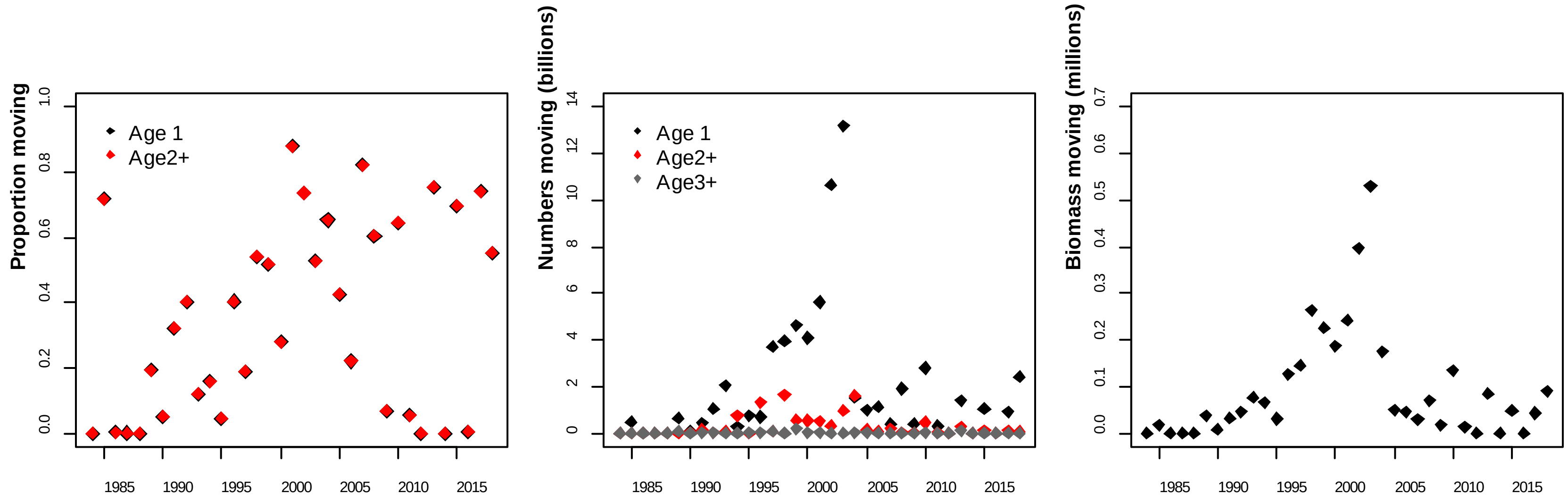


Figure B3. Model estimated proportion of 1-year-olds and 2+-year-olds which move from the "west" component to the "south" component in November. The middle plot shows the numbers of 1-, 2- and 3-year olds moving while the right hand plot shows rough estimates of the annual biomass moving from the west to south component.

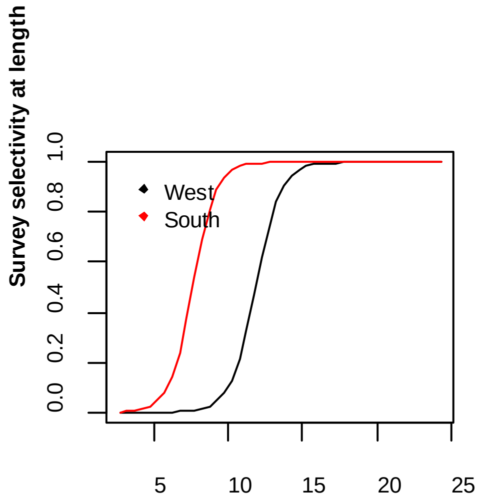


Figure B4. The model estimated November survey selectivity at length.

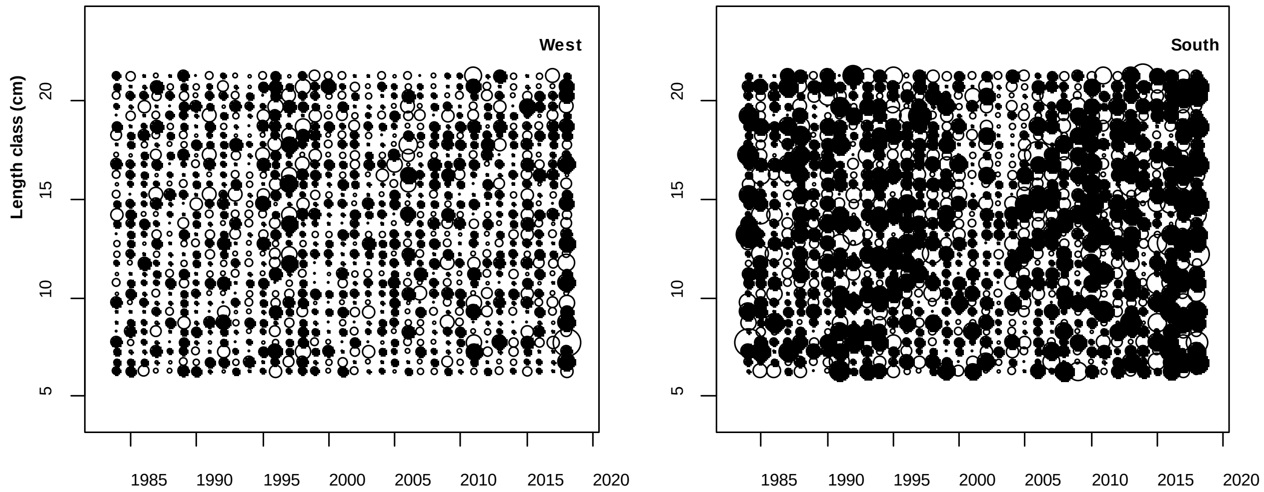


Figure B5. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions.

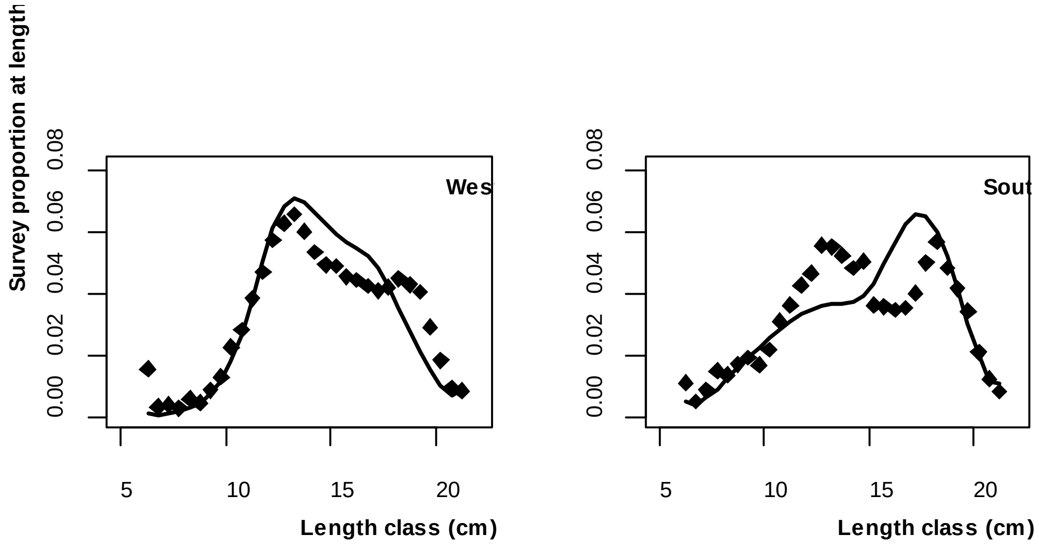


Figure B6. Average (over all years) model predicted and observed proportion-at-length in the November survey.

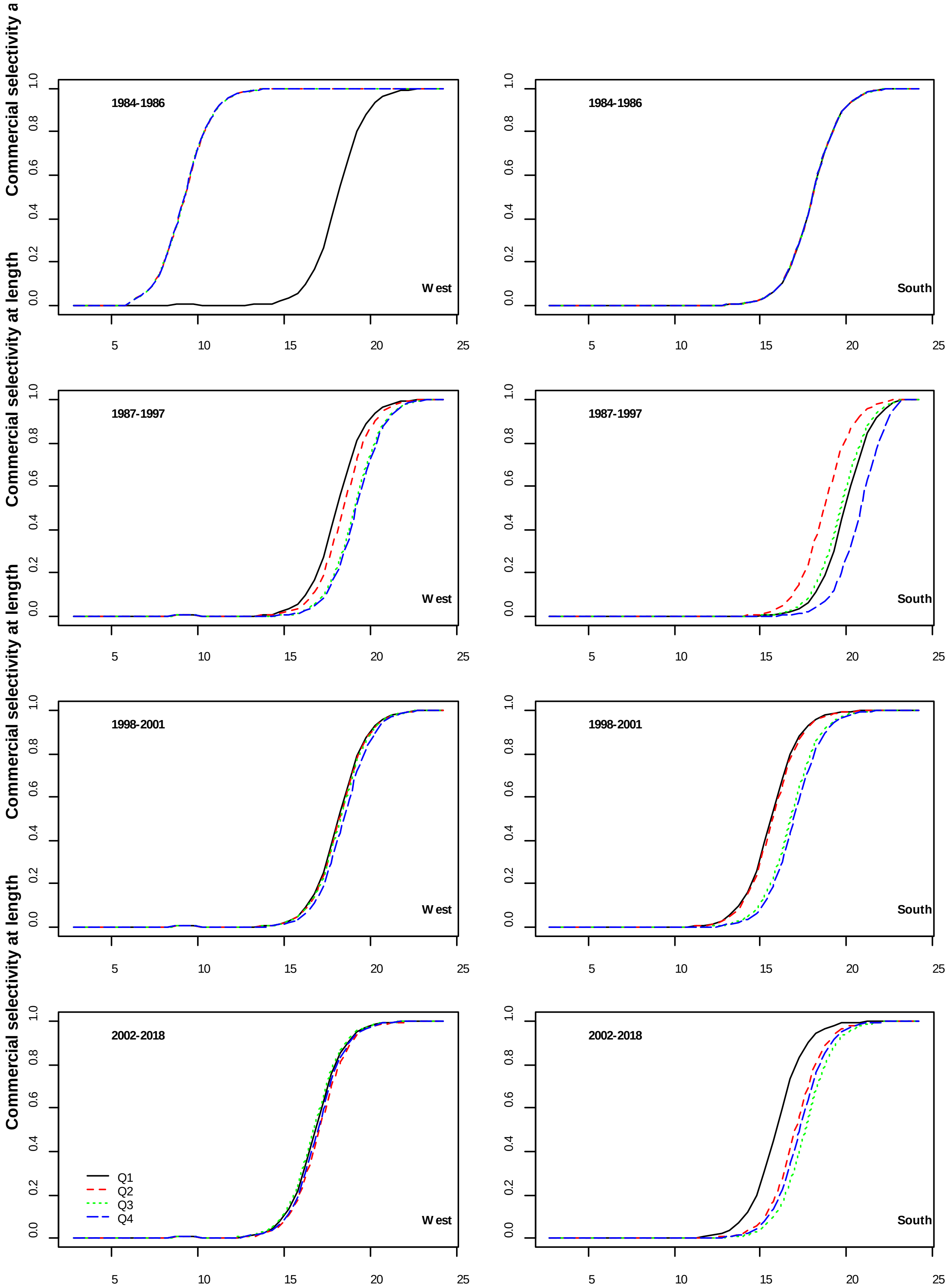


Figure B7. The model estimated commercial selectivity at length, which differs between four pre-specified time periods (the four rows) and quarters.

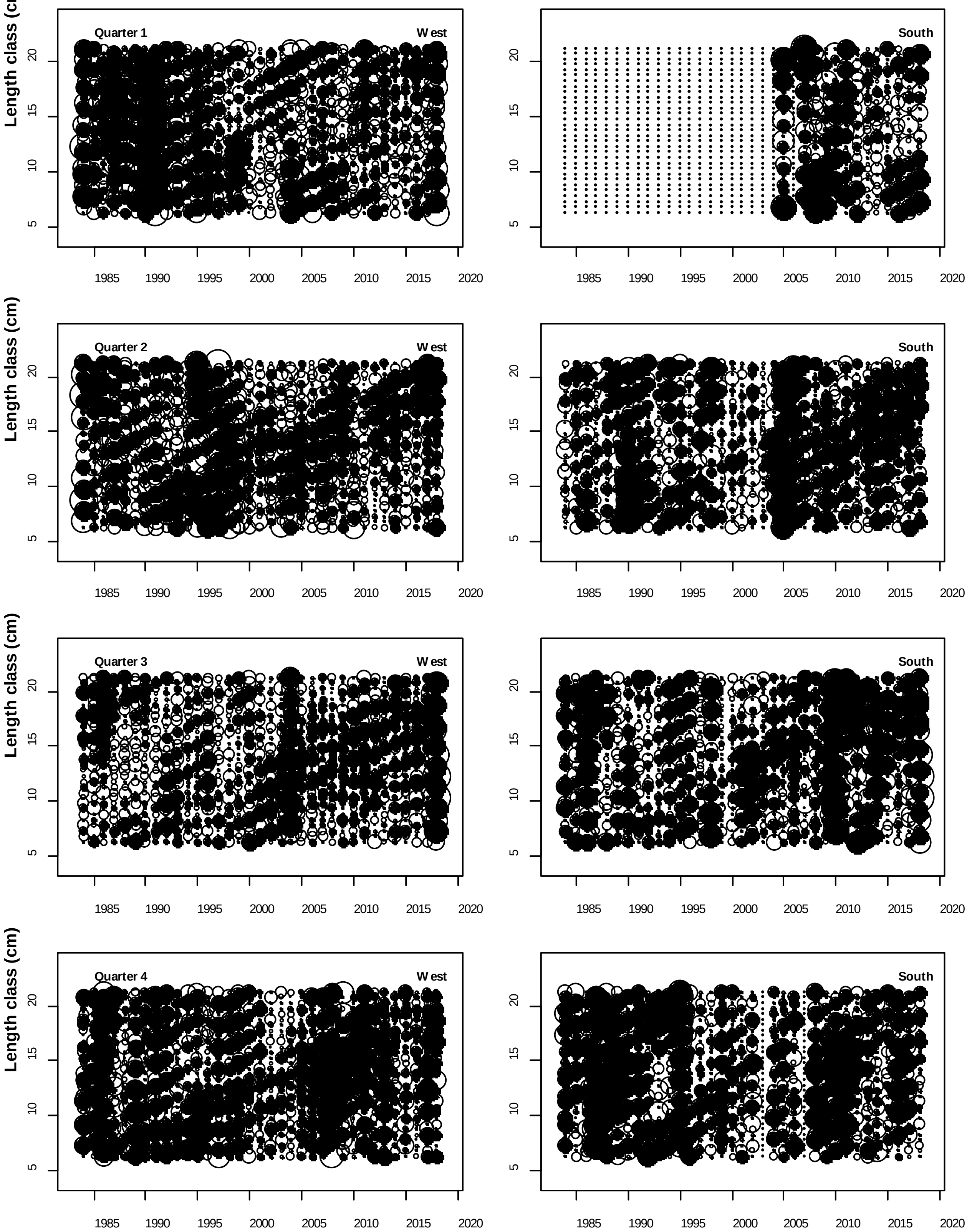


Figure B8. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions.

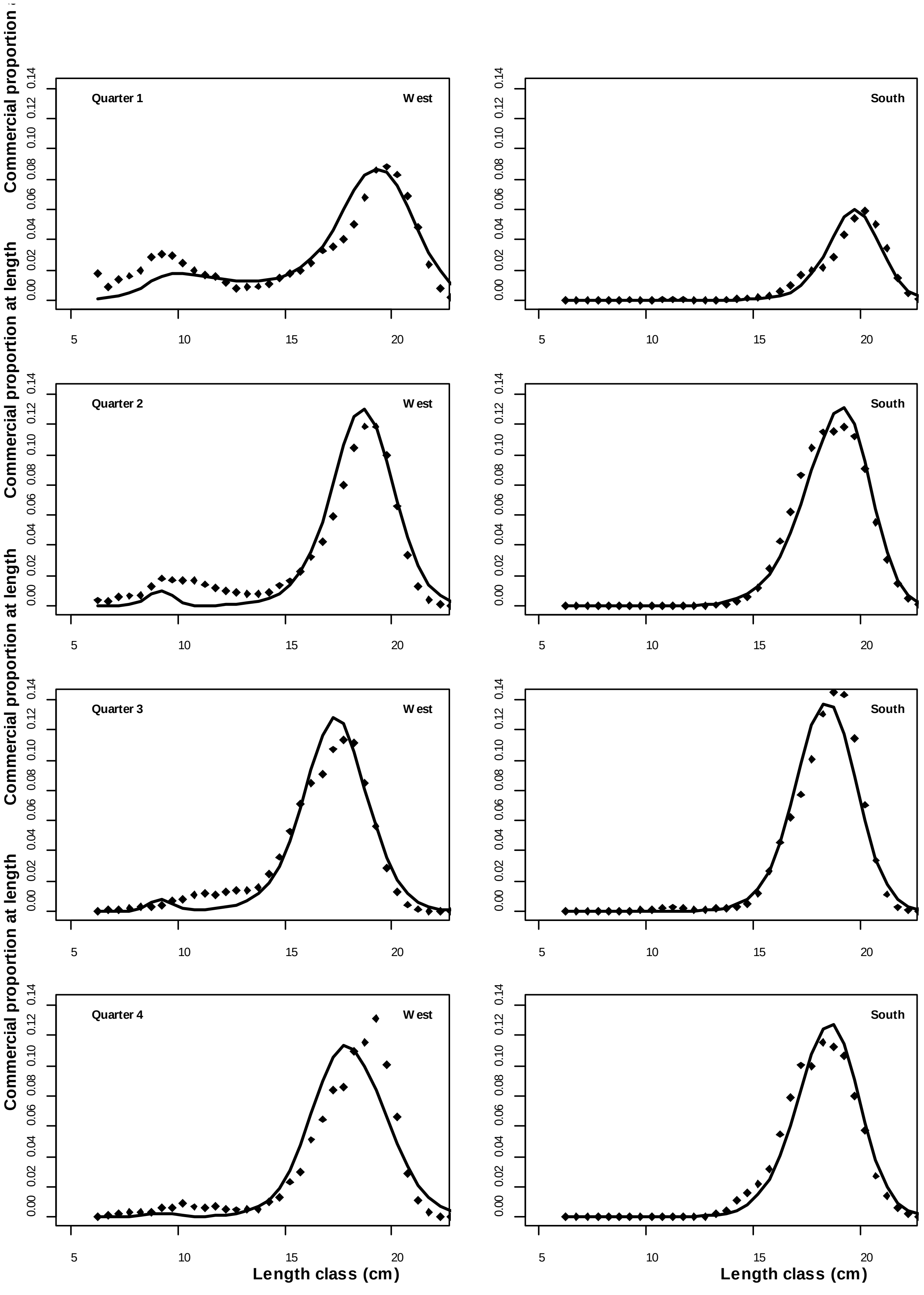


Figure B9. Average (over all quarters and years) model predicted and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted and observed proportions-at-length in the commercial catch (subsequent rows).

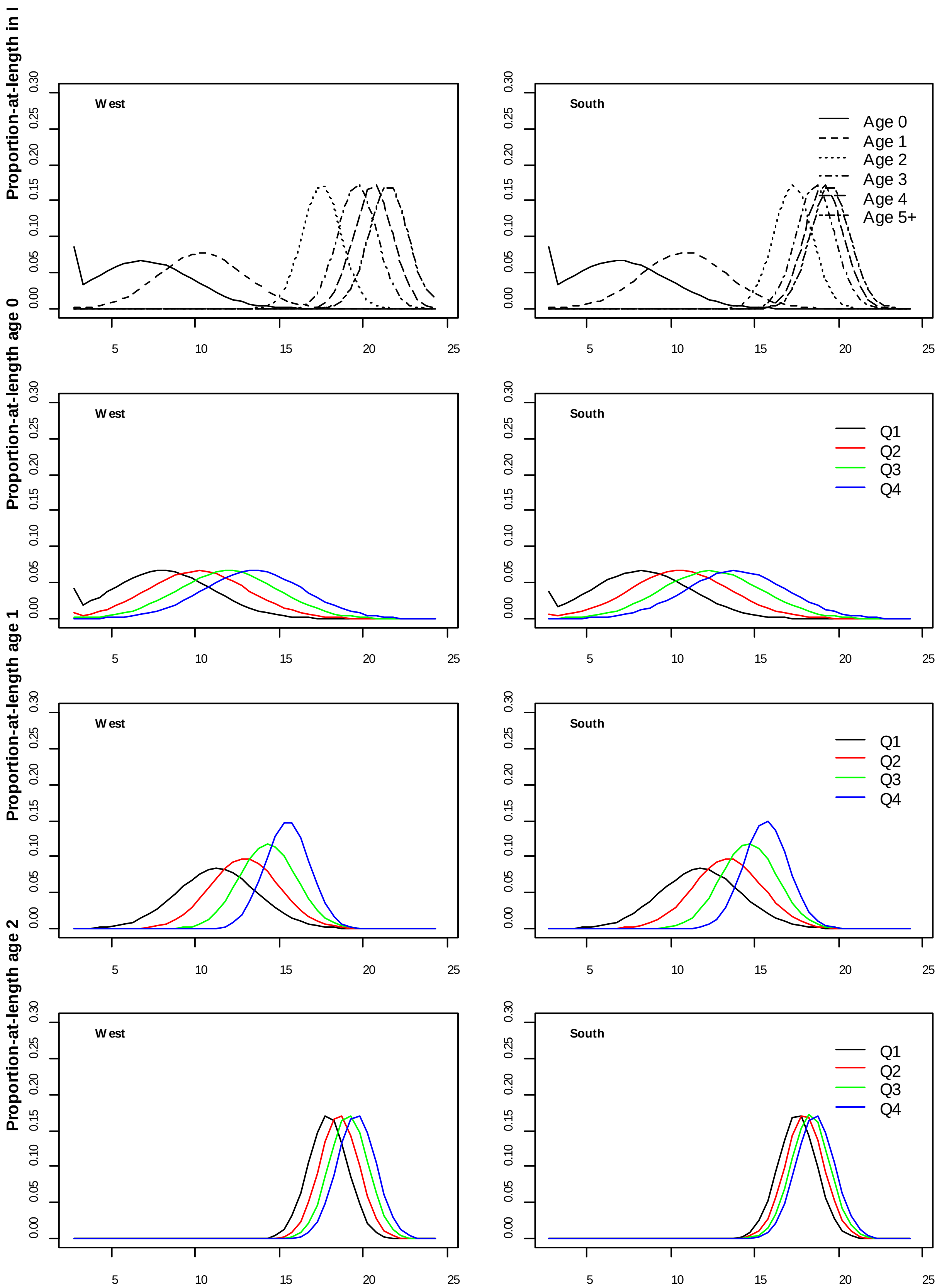


Figure B10. The model estimated distributions of proportions-at-length for each age **in 2010**, given at the time of the biomass survey (1 November, top row), and middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken) for age 0, 1 and 2 (subsequent rows).

Figure B11. The model estimated proportion of west component sardine infected with the parasite between 2008 and 2018. (Annual infection rate is arbitrarily assumed to be 0 prior to 2008.)

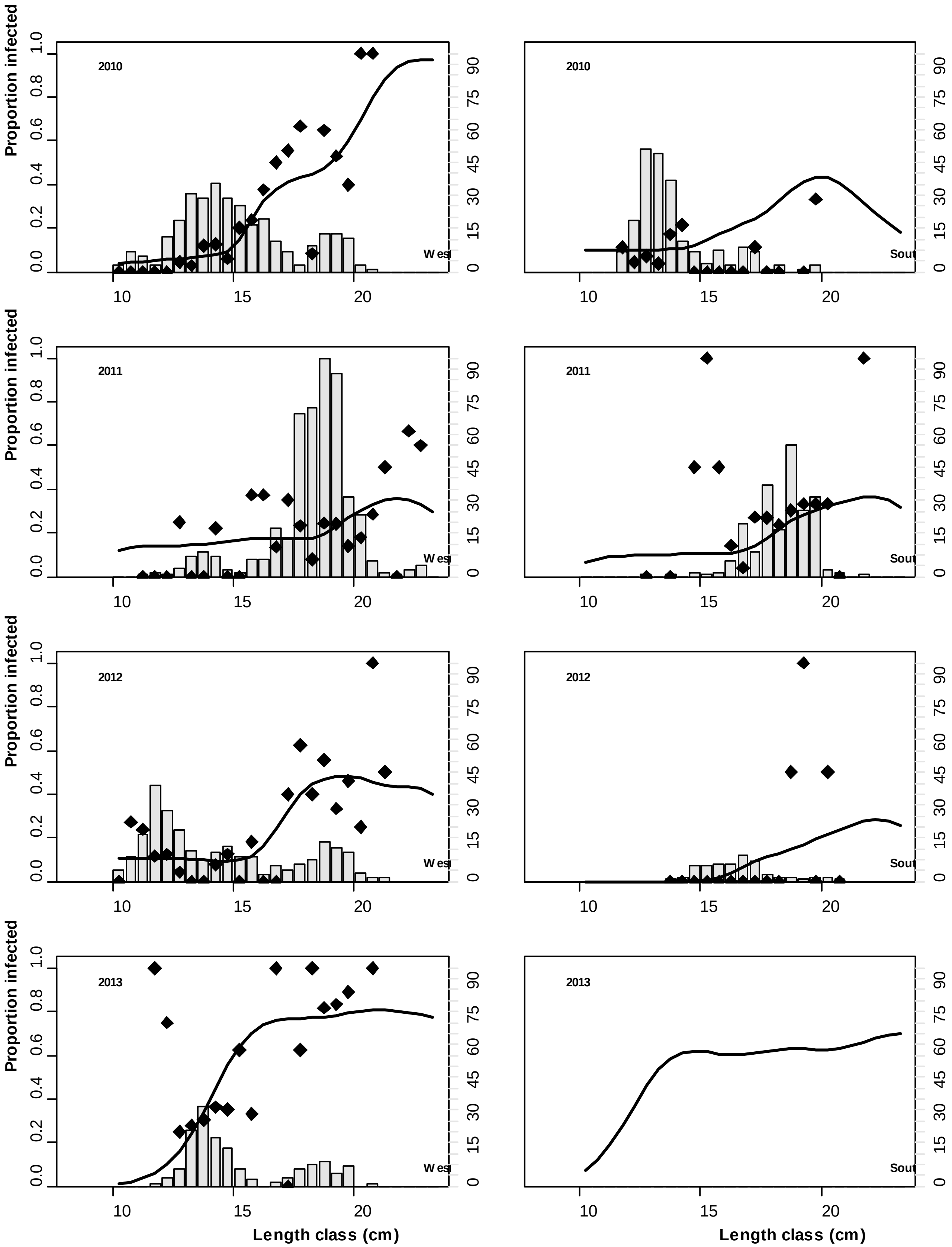


Figure B12. The model estimated proportions-at-length of west and south stock sardine infected with the parasite (i.e. parasite prevalence-by-length) between 2010 and 2018 together with the observed proportions-at-length. The sample size for each length class is given by the grey bars, plotted against the right vertical axis.

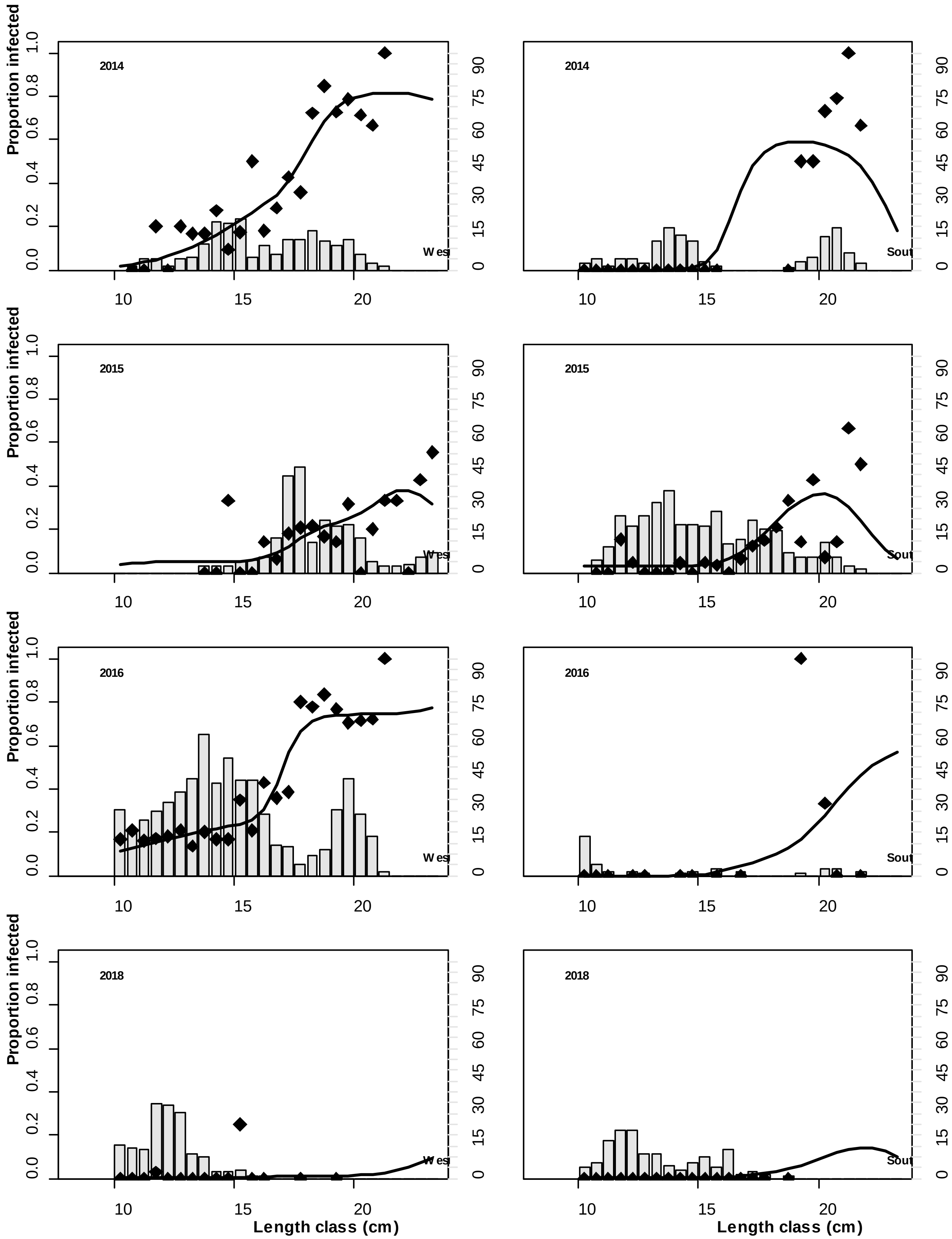


Figure B12 (continued).

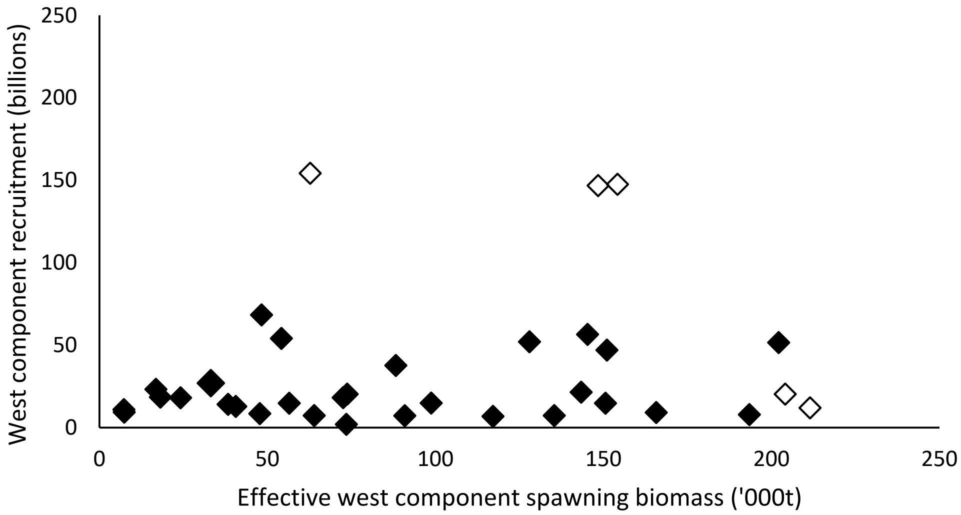


Figure B13. Model predicted sardine recruitment (in November) plotted against effective spawner biomass from November 1984 to November 2017.

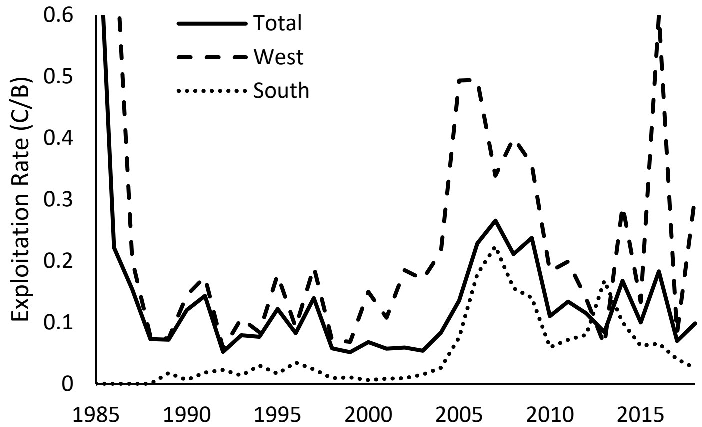


Figure B14. The exploitation rate (simply calculated as the observed annual (Nov-Oct) catch tonnage as a proportion of the model predicted total biomass).

Appendix C: Baseline projections using constant catch assumptions (from de Moor 2019c)

The projections were run from November $y_1 = 2018$ to November $y_n = 2040$. The notation is the same as that of Appendix A and Tables A1 and A2. The following assumptions were made:

- The numbers-at-age were calculated as follows:

$$N_{j,p,y,a}^{S*} = \left(N_{j,p,y-1,a-1}^{S} e^{-M_{y,a-1}^{S}/2} - C_{j,p,y,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/2} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(C1)}$$

$$N_{j,p,y,5^+}^{S*} = \left(N_{j,p,y-1,4}^{S} e^{-M_{y,4}^{S}/2} - C_{j,p,y,4}^{S}\right) e^{-M_{y,4}^{S}/2} + \left(N_{j,p,y-1,5^+}^{S} e^{-M_{y,5^+}^{S}/2} - C_{j,p,y,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/2}$$

$$p = I, NI,\ y_1 \le y \le y_n \qquad \text{(C2)}$$

and

$$\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S}} = \left(1 - \mathrm{move}_{\mathrm{y,a}}\right)\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+$$

$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S**}} + \mathrm{move}_{\mathrm{y,a}}\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(C3)}$$

- Future infection was assumed to be zero (this is inconsequential to projections)
- Future movement of 1-year olds from the west to the south component was assumed to be time-invariant and $\mathrm{move}_{\mathrm{y,1}}$ =0.3, which is roughly the average estimated for the past 5 and 10 years[17]. Additionally, if a density-dependent hypothesis were assumed (de Moor e*t al.* 2018), one would expect movement in the short-term to be relatively low.
- Future recruitment was generated from the past 5[18] years of recruitment under the assumption that future recruitment, particularly in the immediate short-term future, may be from a similar 'regime' to that of the more recent 5 years. For example, recruitment may depend more on environmental conditions rather than on spawning stock biomass (Szuwalski *et al*. 2019). Autocorrelation in the historical recruitment time series is non-negligible lending further weight to this being a preferred baseline choice for these analyses.
- Natural mortality was assumed to be time-invariant: $M_{y,a=0}^{S} = \bar{M}_{ju}^{S}$ and $M_{y,a=1+}^{S} = \bar{M}_{ad}^{S}$
- No allowance was made for early/late recruitment in future years, i.e. $\varepsilon_y^t = 0$ in equation (A8).
- Growth curves at the mid-point of each quarter (equation A17) and therefore the quarterly commercial selectivity-at-age functions (equation A16) were the same[19] for all future years.
- Growth curves in November (equation A7) were thus also the same for all future years.
- Future annual selectivity-at-age was assumed to be time-invariant and averaged over all quarters of the most recent commercial selectivity-at-length estimated from 2002-2018 (note growth curves are time-invariant in future years):

$$S_{j,a}^{S} = 0.25 \sum_{q=1}^{4} \sum_{l=2.5^-}^{24^+} A_{j,2019,q,a,l}^{com} S_{j,2018,q,l} = 0.25 \quad 0 \le a \le 5^+ \qquad \text{(C4)}$$

- The numbers-at-length were calculated according to equations (A5) and (A6).
- The same maturity-at-length relationship, based on that corresponding to the period 1965-1975, was assumed from 2004 onwards, for all projected years.
- The November biomass, spawner biomass and effective spawner biomass were calculated according to equations (A11) to (A13).

[17] November 2018 was excluded as there are fewer data to reliably inform the estimate. The averages over the past 5 and 10 years were 0.36 and 0.44, respectively.
[18] The most recent 5 or 10 years are frequent choices for the "recent past" in projection analyses internationally.
[19] Except in cases where the selectivity is modified to allow catch to be spread to lower ages (described below).

- Figures C1 and C2 indicate the weight-at-length in November 2018 was substantially lower than other years for the west component. For future years, the weight-at-length is assumed to be given by

$$w_{j,y,l}^{S} = a_{j,y} l^{b}, \text{ where } a_{j,y} - \bar{a}_j = \rho_j\left(a_{j,y-1} - \bar{a}_j\right) + \sqrt{1-\rho_j^2}\, a_{j,y}^{*} \tag{C5}$$

where $a_{j,y}^{*}$ is drawn randomly from the historical set of $a_{j,y} - \bar{a}_j$'s obtained by fitting $a_{j,y} l^{b}$ to the $w_{j,y,l}^{S}$ estimated by the assessment for $1984 \leq y \leq 2018$ for the west component and $2008 \leq y \leq 2018$[20] for the south component (Figures C2 and C3). The future $a_{j,y}$ generated in this manner are constrained by the minimum and maximum of the historically estimated $a_{j,y}$'s.

- Catch weight-at-age is taken to be the average of the weight-at-age in November immediately before and after the pulse fishery is assumed, i.e.

$$w_{j,y,a}^{catch} = 0.5\left(w_{j,y-1,a}^{S} + w_{j,y,a+1}^{S}\right) \quad 0 \leq a \leq 4$$

$$w_{j,y,5^+}^{catch} = 0.5\left(w_{j,y-1,5^+}^{S} + w_{j,y,5^+}^{S}\right) \tag{C6}$$

where

$$w_{j,y,a}^{S} = \sum_{l=2.5^-}^{l=24^+} A_{j,y,a,l}^{sur} w_{j,y,l}^{S} \tag{C7}$$

- Catch was assumed to be taken in a single pulse, mid-way through the year. Bycatch was calculated as:

$$C_{j,p,y,a}^{bycatch} = \frac{Bycatch}{\sum_{a=0}^{1}\sum_{p=I,NI} N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} w_{j,a}^{catch}} \times N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} \leq N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2}$$

And directed catch (taken to include large sardine bycatch) was calculated as:

$$C_{j,p,y,a}^{dir} = \frac{Directed+Large\ Bycatch}{\sum_{a=0}^{5^+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times \left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} \text{ , with}$$

$$\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{5^+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,5}^{S} \leq 0.95$$

$$C_{j,p,y,a}^{S} = C_{j,p,y,a}^{bycatch} + C_{j,p,y,a}^{dir} \qquad p = I, NI, y > y_n, 1 \leq q \leq 4, 0 \leq a \leq 5^+ \tag{C8}$$

- In cases where the above constraints would otherwise result in the realised catch being less than the tested scenario, the selectivity was modified as follows:

If $\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{5^+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,5}^{S} \leq 0.95$

Then $C_{j,p,y,5+}^{dir} = 0.95\left(N_{j,p,y-1,5+}^{S} e^{-M_{y,5+}^{S}/2} - C_{j,p,y,5+}^{bycatch}\right)$

If $\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{4}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,4}^{S} \leq 0.95$

Then $C_{j,p,y,4}^{dir} = 0.95\left(N_{j,p,y-1,4}^{S} e^{-M_{y,4}^{S}/2} - C_{j,p,y,4}^{bycatch}\right)$

Else $C_{j,p,y,a<5}^{dir} = \frac{Directed+Large\ Bycatch}{\sum_{a=0}^{3}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times \left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S}$

If $\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{3}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,3}^{S} \leq 0.95$

Then $C_{j,p,y,3}^{dir} = 0.95\left(N_{j,p,y-1,3}^{S} e^{-M_{y,3}^{S}/2} - C_{j,p,y,3}^{bycatch}\right)$

[20] A shorter time frame is used for the south component due to the apparently lower a's in more recent years compared to the full time series (Figure A2).

Else $C^{dir}_{j,p,y,a<4} = \frac{Directed+Large\ Bycatch}{\sum_{a=0}^{3}\sum_{p=I,NI}\left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2}-C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}w^{catch}_{j,a}} \times \left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}$

If $\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{2}\sum_{p=I,NI}\left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2}-C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}w^{catch}_{j,a}} \times S^S_{j,2} \le 0.95$

Then $C^{dir}_{j,p,y,2} = 0.95\left(N^S_{j,p,y-1,2}e^{-M^S_{y,2}/2} - C^{bycatch}_{j,p,y,2}\right)$

$C^{dir}_{j,p,y,a<2} = \frac{Directed+Large\ Bycatch}{\sum_{a=0}^{1}\sum_{p=I,NI}\left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2}-C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}w^{catch}_{j,a}} \times \left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}$, with

$\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{1}\sum_{p=I,NI}\left(N^S_{j,p,y-1,a}e^{-M^S_{y,a}/2}-C^{bycatch}_{j,p,y,a}\right)S^S_{j,a}w^{catch}_{j,a}} \times S^S_{j,5} \le 0.95$ [21]

Estimation of the hockey-stick stock recruitment relationship

November recruitment to stock j in year y was calculated as follows for all years except the pulse west component years of 2000-2004:

$$N^{pred}_{j,y} = \begin{cases} a^S_j & if\ SSB^{eff,S}_{j,y} \ge b^S_j \\ a^S_j \frac{SSB^{eff,S}_{j,y}}{b^S_j} & if\ SSB^{eff,S}_{j,y} < b^S_j \end{cases}$$

The parameters a^S_j, the maximum recruitment of component j in the hockey stick model, and b^S_j, the effective spawner biomass below which the expectation for recruitment is reduced below the maximum for component j were estimated by minimising

$$-lnL = \sum_{y=1984}^{2017}\sum_j\left[ln(\sigma^S_j) + \frac{\left(ln\left(N^S_{j,NI,y,0}\right)-ln\left(N^{pred}_{j,y}\right)\right)^2}{2\left(\sigma^S_j\right)^2}\right]$$

where $\sigma^S_W = \frac{1}{29}\sum_y\left(ln\left(N^S_{W,NI,y,0}\right) - ln\left(N^{pred}_{W,y}\right)\right)^2$ and $\sigma^S_S = \frac{1}{29}\sum_y\left(ln\left(N^S_{S,NI,y,0}\right) - ln\left(N^{pred}_{S,y}\right)\right)^2$.

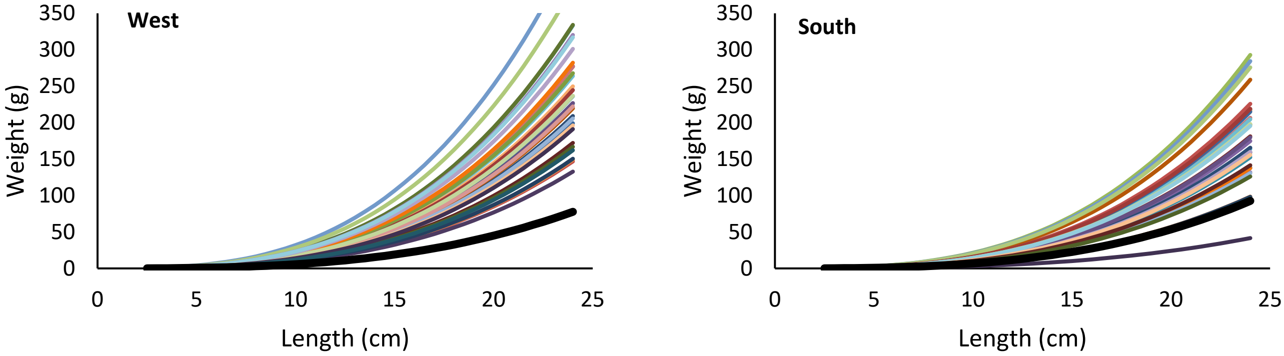


Figure C1. The annual weight-at-length estimated by de Moor (2019b). The dark line denotes 2018.

[21] There are still a few cases where the full catch is not realised by this equation reaching the constraint, even after the modifications to the selectivity are done.

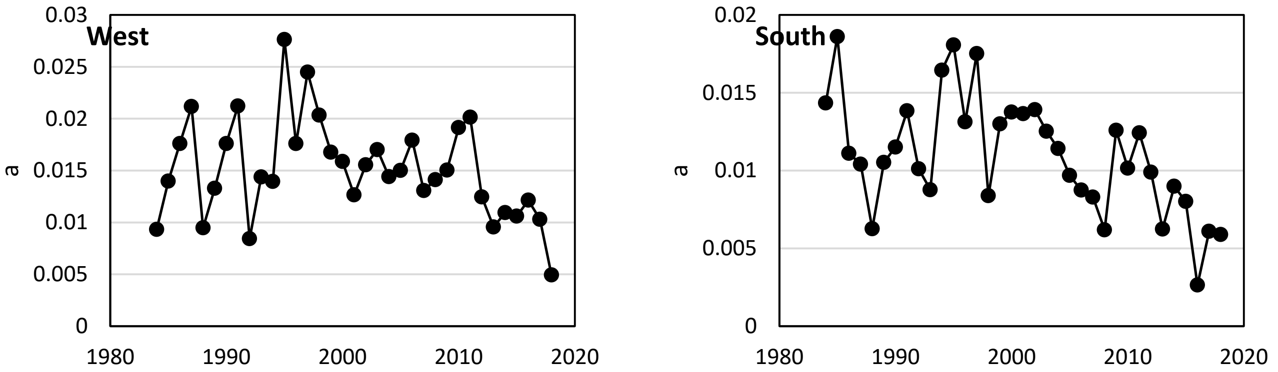


Figure C2. The $a_{j,y}$ values estimated by fixing $b = 3.031$ and fitting to the historically estimated annual weight-at-length using sum of squares. The historical averages are 0.015 for the west component and 0.008 for the south component.

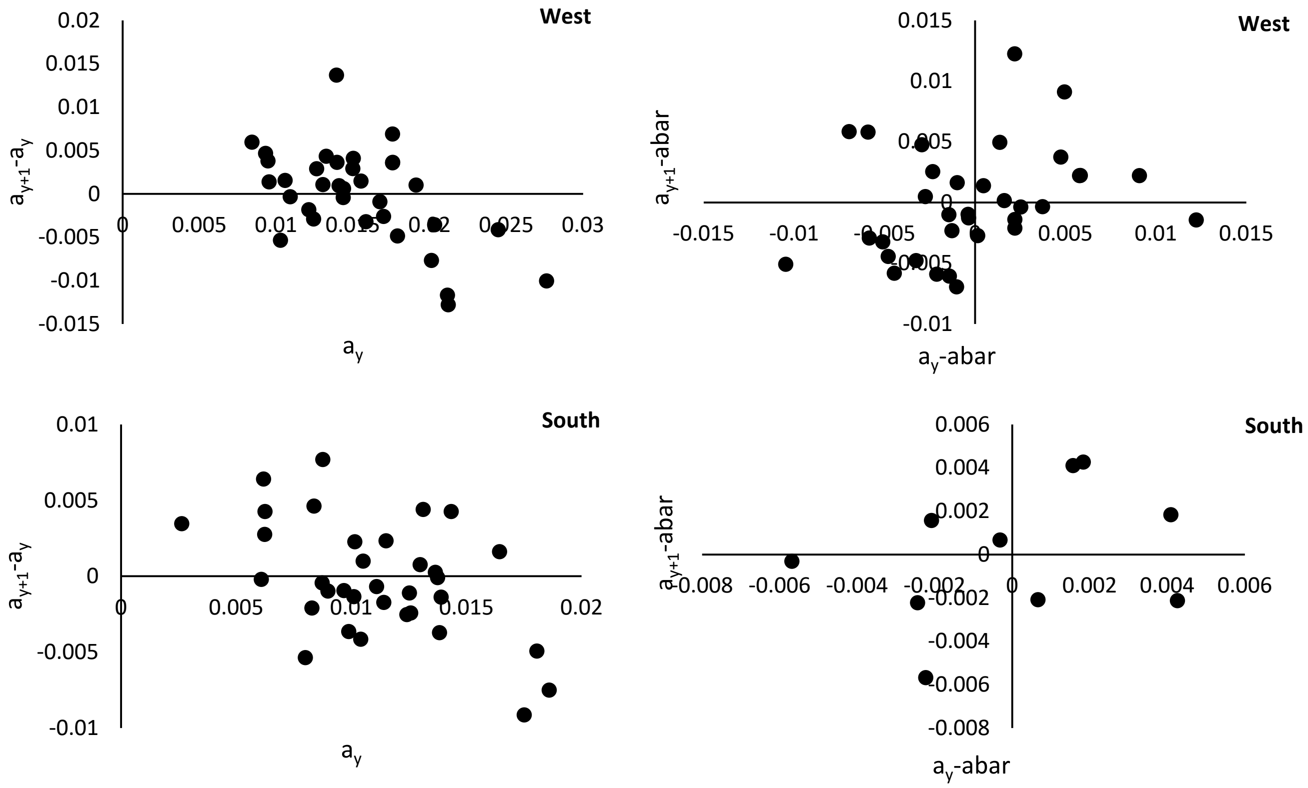


Figure C3. Plots to assess autocorrelation in the $a_{j,y}$'s from Figure C2. The upper plots include all data points, whereas in the lower plot for the south only the data points from 2008-2018 are included. The averages exclude the final year: $\bar{a}_{west} = \sum_{1984}^{2017} a_{west,y} = 0.015$ and $\bar{a}_{south} = \sum_{2008}^{2017} a_{south,y} = 0.008$. The autocorrelation coefficient is estimated as $\rho_{west} = 0.291$ and $\rho_{south} = 0.314$.

Appendix D: An alternative survey length frequency for November 2018 (from Coetzee 2019)

The raised length frequency of sardine derived from trawls conducted during the November 2018 biomass survey was dominated by small sardine, less than 16 cm in length. Length frequencies sampled at field stations from commercial catches landed between October and December both on the West Coast and the South Coast were, however dominated by sardine > 16 cm in length (Figure D1). Whereas it is expected that the commercial length frequency of sardine is under-representative of smaller fish, given that industry would avoid fish smaller than 14 cm (Lt ~ 12 cm Lc) in line with bycatch restrictions and optimising canning outputs, the almost complete lack of >16 cm sardine in the survey trawl catches suggests undersampling of larger sardine during the survey.

Fish are known to avoid trawls, either vertically or horizontally and larger, faster fish are generally more capable of avoiding than smaller fish. Given that the reflectivity (Target Strength, TS) of fish is size dependent, the determination of biomass and population length structure is dependent on representative mid-water trawl sampling of the length frequency of targets that give rise to the measured echo strength. The weight-normalised Target Strength (TS) per kg of fish decreases with increasing fish length and for an 18 cm sardine is about half that of a 12 cm sardine (2.64 dB lower).

Acoustic area density ρ (kg m^{-2}) of species *j* is $\rho_j = \frac{S_{A\,j}}{4\pi.1852^2\left(\bar{\sigma}_{kg_j}\right)}$, where $S_{A\,j}$ is the acoustic energy (Nautical area scattering coefficient, m^2 nm^{-2}) attributed to species *j* and $\bar{\sigma}_{kg_j}$ is the mean backscattering cross section for species *j*, derived from the length frequency as follows: $\bar{\sigma}_{kg_j} = \frac{\sum n_{ij}.10^{0.1b}.l_{ij}^{\frac{a}{10}}}{\sum n_{ij}}$ and where: l_i = length class *i;* n_i = number of fish in length class *i* and b and a are constants in the TS_{kg} versus length relationship.

It is therefore expected that avoidance of the trawl by larger fish will lead to an underestimate of density and biomass, an overestimate of fish numbers and consequently also an underestimate of average fish weight. To estimate the consequences arising out of a suspected under-sampling of larger sardine during the survey, a combined average LF distribution (equal weighting for survey and commercial LFs) was calculated separately for the West Coast and the South Coast (Figure D2) and used instead of the trawl length frequency to derive mean stratum densities by keeping the total acoustic energy $S_{A\,j}$ constant for that stratum.

Stratum densities were converted to biomass and summed for the West and South Coasts to produce a revised biomass estimate for each coast while the combined proportion at length for each coast was weighted by the revised biomass estimate for that coast to derive revised numbers at length for each coast.

Revised estimates of biomass and numbers of sardine, assuming an increase in biomass of 50% (based on initial calculations for one stratum Coetzee 2019) as well as for the constant energy approach detailed above are shown in Table D1 for the combined survey and commercial length frequency while the different biomass (original, x1.5, revised) weighted length frequencies for the combined survey and commercial proportion at length are shown in Figure D3.

Table D1. Comparison of the original survey biomass, original survey biomass x1.5 and revised survey estimate of biomass and number of sardine.

West	Biomass (t)	Revised/original	Numbers	Revised/original
Original Biomass	34845.23		2.49E+09	
Original biomass*1.5	52267.85	1.5	1.17E+09	0.47
Revised biomass	57448.16	1.65	1.29E+09	0.52
South	Biomass (t)	Revised/original	Numbers	Revised/original
Original Biomass	55922.42		2.39E+09	
Original biomass*1.5	83883.63	1.5	1.71E+09	0.72
Revised biomass	75667.99	1.35	1.54E+09	0.65

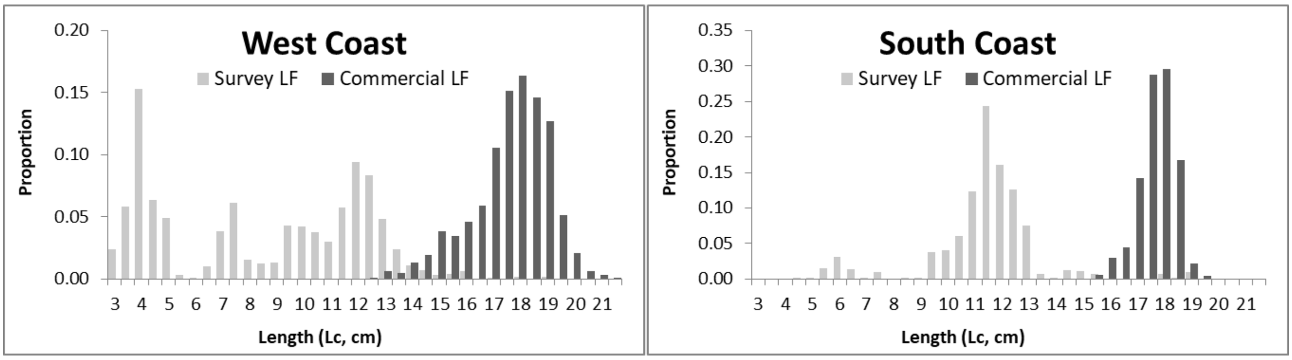


Figure D1. Rasied length frequency obtained from trawls conducted during the November 2018 survey and commercial samples landed between October-December 2018 for the West Coast and the South Coast.

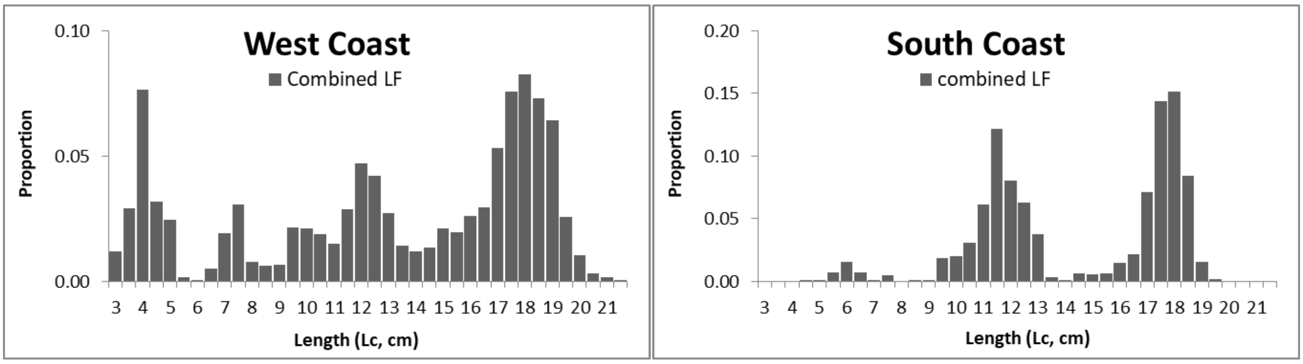
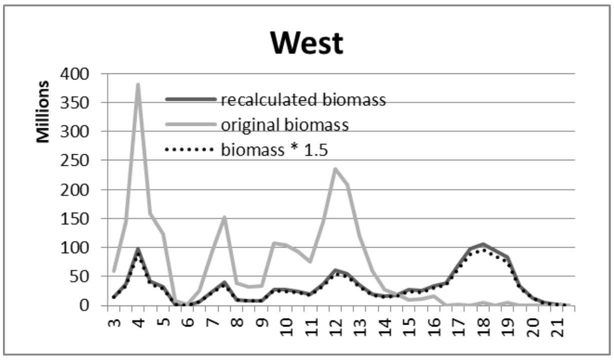


Figure D2. Combined (survey and commercial, Oct-Dec) average raised length frequency for the West Coast and the South Coast.



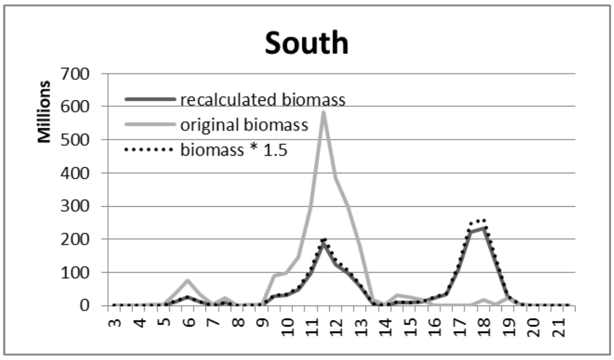


Figure D3. Weighted original survey length frequency and weighted (by recalculated biomass) combined survey and commercial length frequencies for the West and South coasts.

Appendix E: Some results from the short term projections (from de Moor 2019c)

Table E1. The multiplicative increase (or decrease) in effective spawning biomass from November 2018 to November 2019, assuming $\mathrm{move}_{\mathrm{y},1} = 0.3$. Grey cells indicate cases for which the selectivity function needed modification to enable the catch to be taken. Dark grey cells indicate cases for which the full catch could still not be realised after selectivity was modified.

					West component				South component				20% west
Model	Total	West	South	Bycatch	5%ile	20%ile	30%ile	50%ile	5%ile	20%ile	30%ile	50%ile	difference
Alternative A	0	0	0	0	2.87	3.42	3.59	3.83	1.35	1.89	1.98	2.36	
	16.775	**4.575**	**4.2**	**8**	2.53	3.12	3.38	3.69	1.32	1.8	1.93	2.31	**0.88**
	20.75	5.25	5	10.5	2.49	3.05	3.34	3.65	1.32	1.83	1.92	2.30	**0.85**
	23	6.5	7	9.5	2.49	3.04	3.31	3.63	1.31	1.82	1.90	2.29	**0.84**
	26.75	**8.25**	**8**	**10.5**	**2.45**	**2.99**	**3.24**	**3.59**	**1.30**	**1.81**	**1.89**	**2.27**	**0.82**
Alternative B	0	0	0	0	1.70	2.13	2.40	2.83	0.45	0.94	0.94	1.41	
	16.775	4.575	4.2	8	1.49	1.91	2.16	2.61	0.44	0.91	0.92	1.38	**0.81**
	20.75	5.25	5	10.5	1.43	1.86	2.10	2.55	0.44	0.91	0.91	1.38	**0.76**
	23	6.5	7	9.5	1.43	1.85	2.09	2.53	0.43	0.90	0.90	1.37	**0.75**
	26.75	8.25	8	10.5	1.39	1.81	2.05	2.48	0.43	0.89	0.90	1.36	**0.72**
Baseline	0	0	0	0	2.20	2.67	2.95	3.40	0.45	1.05	1.05	1.55	
	16.775	4.575	4.2	8	1.96	2.44	2.70	3.17	0.44	1.02	1.03	1.52	**0.86**
	20.75	5.25	5	10.5	1.90	2.38	2.64	3.12	0.44	1.02	1.02	1.52	**0.83**
	23	6.5	7	9.5	1.88	2.36	2.62	3.09	0.44	1.01	1.02	1.51	**0.82**
	26.75	8.25	8	10.5	1.83	2.32	2.57	3.03	0.43	1.01	1.01	1.50	**0.79**
Alternative C	0	0	0	0	1.08	1.38	1.47	1.68	0.31	0.74	0.76	1.15	
	16.775	4.575	4.2	8	0.94	1.24	1.33	1.55	0.30	0.72	0.75	1.13	**0.65**
	20.75	5.25	5	10.5	0.91	1.21	1.30	1.52	0.30	0.72	0.75	1.13	**0.57**
	23	6.5	7	9.5	0.89	1.20	1.29	1.50	0.30	0.71	0.74	1.12	**0.53**
	26.75	8.25	8	10.5	0.86	1.17	1.26	1.47	0.30	0.71	0.74	1.12	**0.44**

It is important to note that the "directed" catches modelled in this analysis were taken to include all large sardine catch and bycatch, as well as small sardine bycatch with the directed sardine fishery. The "bycatches" modelled in this analysis were taken to include small sardine bycatch with anchovy and round herring. Thus if, for example, the option of 5250t directed west – 5000t directed south – 10500t bycatch was selected from the above table to inform quota recommendations, the 5250t would need to allow for the directed sardine TAC west of Cape Agulhas, the associated small sardine TAB and large sardine TAB with round herring and anchovy, while the 10500t would need to allow for small sardine TAB with anchovy and small sardine TAB with round herring.

Table E2a. The additive increase (or decrease) in effective spawning biomass (in '000t) from November 2018 to November 2019, assuming $\mathrm{move}_{y,1} = 0.3$. Grey cells indicate cases for which the selectivity function needed modification to enable the catch to be taken. Dark grey cells indicate cases for which the full catch could still not be realised after selectivity was modified.

					West component				South component				20% west
Model	Total	West	South	Bycatch	5%ile	20%ile	30%ile	50%ile	5%ile	20%ile	30%ile	50%ile	difference
Old	0	0	0	0	33	56	62	78	28	53	65	102	
	10	3.5	1.5	5	30	53	58	75	27	52	64	100	0.95
	15*	7	3	5	28	51	56	73	26	51	63	99	0.91
	16*	4.575	1.425	10	28	51	56	73	26	52	64	100	0.90
	16.575	4.575	7	5	29	52	57	74	24	50	61	97	0.93
	25*	14	6	5	24	47	53	69	24	49	61	96	0.84
	25*	9	6	10	25	48	54	71	24	50	61	97	0.86
	26.75*	8.25	8	10.5	21	43	49	66	22	47	59	94	0.86
	26.75*	9.25	9	8.5	24	47	52	69	19	44	56	91	0.86
	35*	21	9	5	26	48	54	71	23	49	60	96	0.78
	35	14	16	5	26	48	54	71	23	48	60	95	0.83
Revised	0	0	0	0	15	24	29	38	-70	-8	-8	53	
	10	3.5	1.5	5	12	21	26	35	-70	-10	-9	51	0.86
	15	7	3	5	10	19	24	33	-71	-11	-10	50	0.80
	16	4.575	1.425	10	10	19	24	32	-71	-10	-9	51	0.78
	16.575	4.575	7	5	11	20	25	34	-72	-12	-12	48	0.83
	25	14	6	5	8	17	22	30	-72	-13	-12	48	0.71
	25	9	6	10	8	17	22	30	-72	-13	-12	48	0.71
	26.75	8.25	8	10.5	8	17	22	30	-73	-14	-13	47	0.70
	26.75	9.25	9	8.5	8	17	22	30	-73	-14	-13	46	0.72
	35	21	9	5	6	15	20	29	-73	-14	-13	46	0.63
	35	14	16	5	8	17	22	30	-75	-17	-16	42	0.70
Revised, $\rho_j = 0$	0	0	0	0	25	35	40	50	-70	6	6	70	
	10	3.5	1.5	5	22	32	37	46	-70	5	5	69	0.91
	15	7	3	5	20	30	35	44	-71	4	4	68	0.85
	16	4.575	1.425	10	20	29	35	44	-71	4	5	68	0.85
	16.575	4.575	7	5	21	31	36	46	-72	2	2	66	0.88
	25	14	6	5	18	28	33	41	-72	2	2	65	0.79
	25	9	6	10	18	27	33	42	-72	2	2	65	0.78
	26.75	8.25	8	10.5	18	27	33	42	-73	1	1	64	0.78
	26.75	9.25	9	8.5	18	28	33	42	-73	0	1	64	0.79
	35	21	9	5	16	25	31	40	-73	0	1	63	0.73
	35	14	16	5	18	27	32	41	-75	-3	-2	60	0.78
Revised, alt 2018 data, $\rho_j = 0$	0	0	0	0	8	17	23	35	-92	-36	-33	16	
	10	3.5	1.5	5	5	14	20	33	-92	-37	-33	16	0.86
	15	7	3	5	4	13	18	31	-92	-37	-34	15	0.77
	16	4.575	1.425	10	4	13	18	31	-92	-37	-33	15	0.77
	16.575	4.575	7	5	5	14	19	32	-93	-39	-35	13	0.82
	25	14	6	5	1	10	15	29	-93	-39	-35	13	0.60
	25	9	6	10	2	11	16	30	-93	-39	-35	13	0.66
	26.75	8.25	8	10.5	2	11	16	30	-94	-39	-36	12	0.66
	26.75	9.25	9	8.5	2	11	16	30	-94	-40	-36	12	0.66
	35	21	9	5	-2	7	11	25	-94	-40	-37	11	0.42
	35	14	16	5	1	10	14	28	-95	-42	-39	9	0.58

* In these cases the full catch could not be realised in only one out of 100 simulations.

"Old" – Alternative A, "Revised" – Alternative B, "Revised $\rho_j = 0$" – Baseline, "Revised, alt 2018 data, $\rho_j = 0$ " – Alternative C.

Table E2b. The multiplicative increase (or decrease) in effective spawning biomass from November 2018 to November 2019, assuming $\mathrm{move}_{y,1} = 0.3$. Grey cells indicate cases for which the selectivity function needed modification to enable the catch to be taken. Dark grey cells indicate cases for which the full catch could still not be realised after selectivity was modified.

					West component				South component				20% west
Model	Total	West	South	Bycatch	5%ile	20%ile	30%ile	50%ile	5%ile	20%ile	30%ile	50%ile	difference
Old	0	0	0	0	2.87	3.42	3.59	3.83	1.35	1.89	1.98	2.36	
	10	3.5	1.5	5	2.58	3.22	3.45	3.72	1.33	1.86	1.95	2.34	0.92
	15*	7	3	5	2.53	3.12	3.38	3.68	1.33	1.84	1.94	2.32	0.88
	16*	4.575	1.425	10	2.51	3.09	3.36	3.67	1.33	1.85	1.95	2.33	0.86
	16.575	4.575	7	5	2.56	3.17	3.41	3.71	1.31	1.82	1.91	2.30	0.90
	25*	14	6	5	2.37	2.93	3.22	3.54	1.31	1.81	1.90	2.29	0.80
	25*	9	6	10	2.45	2.99	3.24	3.58	1.31	1.82	1.91	2.29	0.82
	26.75*	8.25	8	10.5	2.45	2.99	3.24	3.59	1.30	1.81	1.89	2.27	0.82
	26.75*	9.25	9	8.5	2.46	3.00	3.25	3.59	1.30	1.80	1.88	2.27	0.83
	35*	21	9	5	2.13	2.79	3.06	3.37	1.29	1.78	1.87	2.25	0.74
	35	14	16	5	2.32	2.91	3.20	3.53	1.26	1.72	1.82	2.20	0.79
Revised	0	0	0	0	1.70	2.13	2.40	2.83	0.45	0.94	0.94	1.41	
	10	3.5	1.5	5	1.56	1.98	2.24	2.68	0.45	0.92	0.93	1.40	0.87
	15	7	3	5	1.50	1.92	2.16	2.59	0.44	0.92	0.92	1.39	0.81
	16	4.575	1.425	10	1.46	1.89	2.14	2.58	0.45	0.92	0.93	1.40	0.79
	16.575	4.575	7	5	1.53	1.95	2.20	2.64	0.44	0.90	0.91	1.37	0.84
	25	14	6	5	1.40	1.82	2.07	2.49	0.44	0.90	0.91	1.37	0.73
	25	9	6	10	1.39	1.81	2.05	2.48	0.44	0.90	0.91	1.37	0.72
	26.75	8.25	8	10.5	1.39	1.81	2.05	2.48	0.43	0.89	0.90	1.36	0.72
	26.75	9.25	9	8.5	1.40	1.83	2.06	2.49	0.43	0.89	0.90	1.36	0.73
	35	21	9	5	1.31	1.72	1.98	2.40	0.43	0.89	0.89	1.36	0.64
	35	14	16	5	1.38	1.80	2.04	2.47	0.41	0.86	0.87	1.33	0.71
Revised, $\rho_j = 0$	0	0	0	0	2.20	2.67	2.95	3.40	0.45	1.05	1.05	1.55	
	10	3.5	1.5	5	2.04	2.51	2.78	3.24	0.45	1.04	1.04	1.54	0.91
	15	7	3	5	1.95	2.43	2.69	3.16	0.45	1.03	1.03	1.53	0.86
	16	4.575	1.425	10	1.93	2.42	2.68	3.15	0.45	1.03	1.04	1.53	0.85
	16.575	4.575	7	5	2.00	2.47	2.74	3.20	0.44	1.01	1.02	1.51	0.88
	25	14	6	5	1.84	2.33	2.59	3.02	0.44	1.01	1.02	1.51	0.80
	25	9	6	10	1.83	2.32	2.57	3.03	0.44	1.01	1.02	1.51	0.79
	26.75	8.25	8	10.5	1.83	2.32	2.57	3.03	0.86	1.09	1.20	1.41	0.79
	26.75	9.25	9	8.5	1.85	2.33	2.58	3.04	0.87	1.10	1.20	1.41	0.80
	35	21	9	5	1.77	2.23	2.49	2.93	0.43	1.00	1.01	1.49	0.73
	35	14	16	5	1.83	2.30	2.56	3.00	0.41	0.97	0.98	1.46	0.78
Revised, alt 2018 data, $\rho_j = 0$	0	0	0	0	1.23	1.52	1.69	2.08	0.30	0.72	0.75	1.13	
	10	3.5	1.5	5	1.16	1.44	1.61	2.00	0.30	0.72	0.74	1.12	0.86
	15	7	3	5	1.12	1.40	1.56	1.95	0.30	0.71	0.74	1.11	0.77
	16	4.575	1.425	10	1.12	1.40	1.56	1.96	0.30	0.72	0.74	1.12	0.77
	16.575	4.575	7	5	1.15	1.42	1.59	1.98	0.29	0.70	0.73	1.10	0.82
	25	14	6	5	1.03	1.31	1.45	1.86	0.29	0.70	0.73	1.10	0.60
	25	9	6	10	1.07	1.34	1.49	1.89	0.29	0.70	0.73	1.10	0.66
	26.75	8.25	8	10.5	1.07	1.34	1.49	1.90	0.29	0.70	0.72	1.09	0.66
	26.75	9.25	9	8.5	1.07	1.34	1.49	1.90	0.29	0.70	0.72	1.09	0.66
	35	21	9	5	0.93	1.21	1.35	1.77	0.29	0.69	0.72	1.09	0.41
	35	14	16	5	1.03	1.30	1.44	1.85	0.28	0.68	0.70	1.06	0.57

* In these cases the full catch could not be realised in only one out of 100 simulations.

\# "Old" – Alternative A, "Revised" – Alternative B, "Revised $\rho_j = 0$" – Baseline, "Revised, alt 2018 data, $\rho_j = 0$ " – Alternative C.

Table E2c. The west component effective spawning biomass in November 2019 compared to November 2007 (the risk threshold), assuming $\mathrm{move}_{y,1} = 0.3$. Grey cells indicate cases for which the selectivity function needed modification to enable the catch to be taken. Dark grey cells indicate cases for which the full catch could still not be realised after selectivity was modified.

Model	Total	West	South	Bycatch	5%ile	20%ile	30%ile	50%ile	20% diff
Old	0	0	0	0	1.00	1.80	1.91	2.34	
	10	3.5	1.5	5	0.93	1.72	1.83	2.26	0.95
	15*	7	3	5	0.89	1.68	1.79	2.22	0.93
	16*	4.575	1.425	10	0.88	1.66	1.78	2.21	0.92
	16.575	4.575	7	5	0.91	1.70	1.81	2.24	0.94
	25*	14	6	5	0.80	1.59	1.71	2.13	0.88
	25*	9	6	10	0.83	1.61	1.73	2.16	0.89
	26.75*	8.25	8	10.5	0.83	1.61	1.73	2.16	0.89
	26.75*	9.25	9	8.5	0.83	1.61	1.73	2.16	0.90
	35*	21	9	5	0.72	1.51	1.63	2.05	0.84
	35	14	16	5	0.79	1.58	1.70	2.12	0.88
Revised	0	0	0	0	0.79	1.02	1.11	1.32	
	10	3.5	1.5	5	0.73	0.95	1.04	1.25	0.93
	15	7	3	5	0.69	0.91	1.01	1.21	0.90
	16	4.575	1.425	10	0.68	0.90	1.00	1.20	0.88
	16.575	4.575	7	5	0.71	0.93	1.02	1.23	0.91
	25	14	6	5	0.65	0.87	0.97	1.15	0.85
	25	9	6	10	0.64	0.86	0.96	1.15	0.85
	26.75	8.25	8	10.5	0.64	0.86	0.96	1.15	0.85
	26.75	9.25	9	8.5	0.65	0.87	0.96	1.15	0.85
	35	21	9	5	0.61	0.82	0.92	1.12	0.81
	35	14	16	5	0.64	0.86	0.96	1.14	0.84
Revised, $\rho_j = 0$	0	0	0	0	1.02	1.26	1.37	1.58	
	10	3.5	1.5	5	0.95	1.18	1.30	1.51	0.94
	15	7	3	5	0.91	1.15	1.26	1.47	0.91
	16	4.575	1.425	10	0.90	1.14	1.25	1.46	0.90
	16.575	4.575	7	5	0.93	1.17	1.28	1.49	0.93
	25	14	6	5	0.87	1.09	1.20	1.40	0.86
	25	9	6	10	0.86	1.09	1.20	1.41	0.86
	26.75	8.25	8	10.5	0.86	1.09	1.20	1.41	0.87
	26.75	9.25	9	8.5	0.87	1.10	1.20	1.41	0.87
	35	21	9	5	0.83	1.06	1.16	1.36	0.84
	35	14	16	5	0.86	1.08	1.19	1.39	0.86
Revised, alt 2018 data, $\rho_j = 0$	0	0	0	0	0.91	1.09	1.24	1.53	
	10	3.5	1.5	5	0.86	1.04	1.18	1.47	0.95
	15	7	3	5	0.83	1.00	1.14	1.44	0.92
	16	4.575	1.425	10	0.83	1.01	1.14	1.44	0.92
	16.575	4.575	7	5	0.85	1.02	1.16	1.46	0.94
	25	14	6	5	0.77	0.94	1.06	1.38	0.86
	25	9	6	10	0.79	0.96	1.09	1.40	0.88
	26.75	8.25	8	10.5	0.79	0.97	1.09	1.40	0.88
	26.75	9.25	9	8.5	0.79	0.96	1.09	1.40	0.88
	35	21	9	5	0.70	0.87	0.99	1.31	0.80
	35	14	16	5	0.76	0.93	1.05	1.37	0.85

* In these cases the full catch could not be realised in only one out of 100 simulations.

\# "Old" – Alternative A, "Revised" – Alternative B, "Revised $\rho_j = 0$" – Baseline, "Revised, alt 2018 data, $\rho_j = 0$ " – Alternative C.

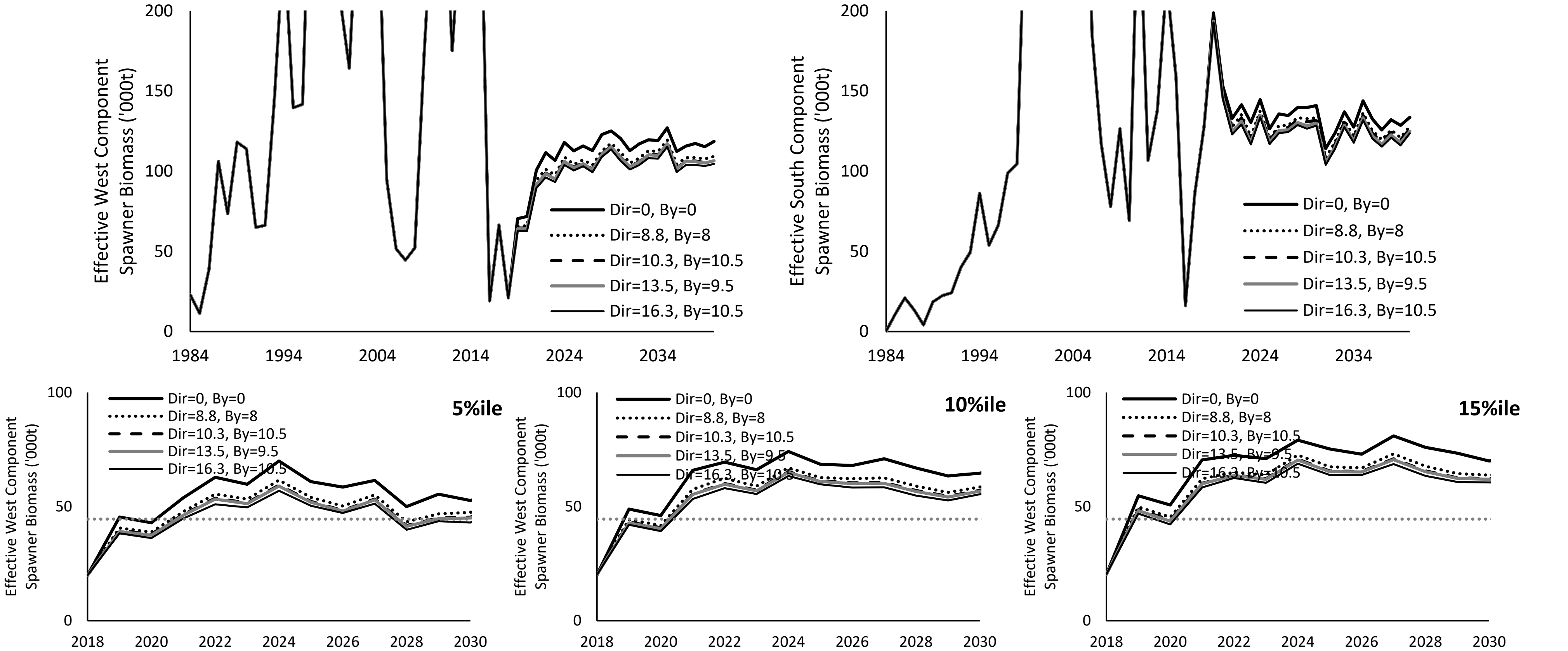


Figure E1a. Effective spawning biomass for the (left) west and (right) south components for projections assuming a range of constant future [west large catch + south large catch, west small bycatch] options, using the baseline model. The upper plots show the median while the lower plots show the 5, 10 and 15%ile for the west component over a narrower range on both axes. The grey dotted line indicates the risk threshold of the 2007 effective west component spawning biomass.

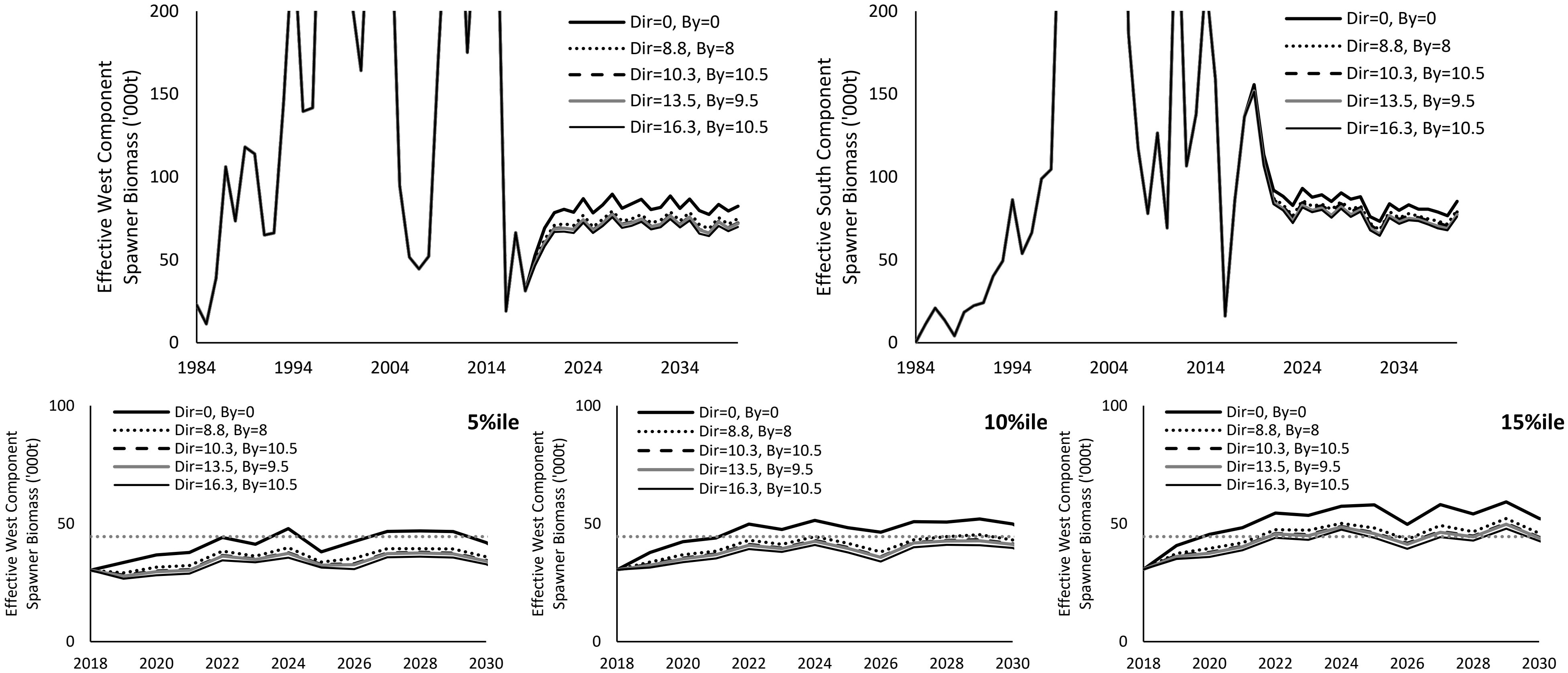


Figure E1b. As for Figure 4a, but using Alternative C.

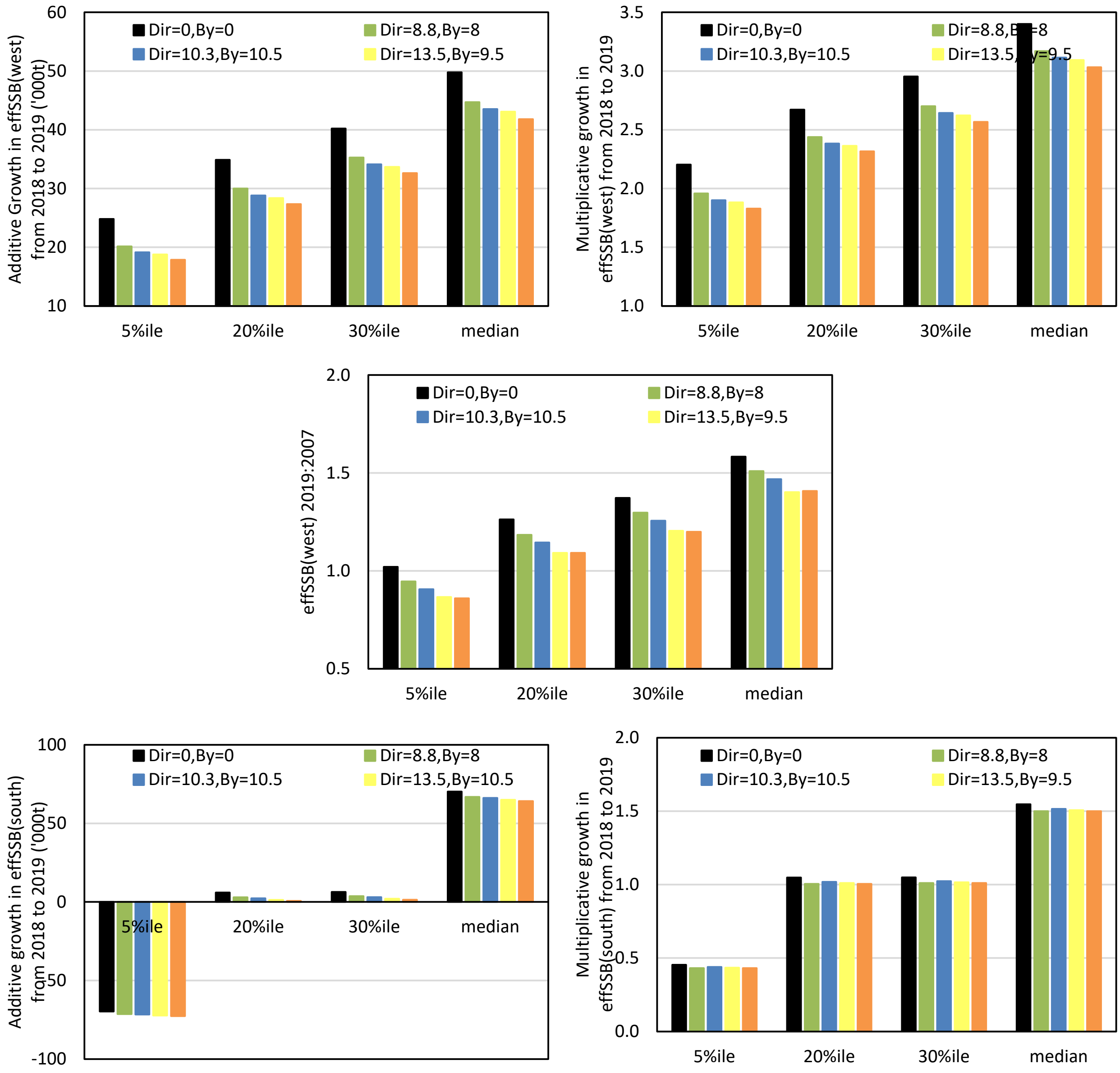


Figure E2. Histograms showing a) the west component effective spawning biomass in 2019-2018, b) the west component effective spawning biomass in 2019:2018, c) the west component effective spawning biomass in 2019:2007, d) the south component effective spawning biomass in 2019-2018, e) the south component effective spawning biomass in 2019:2018.